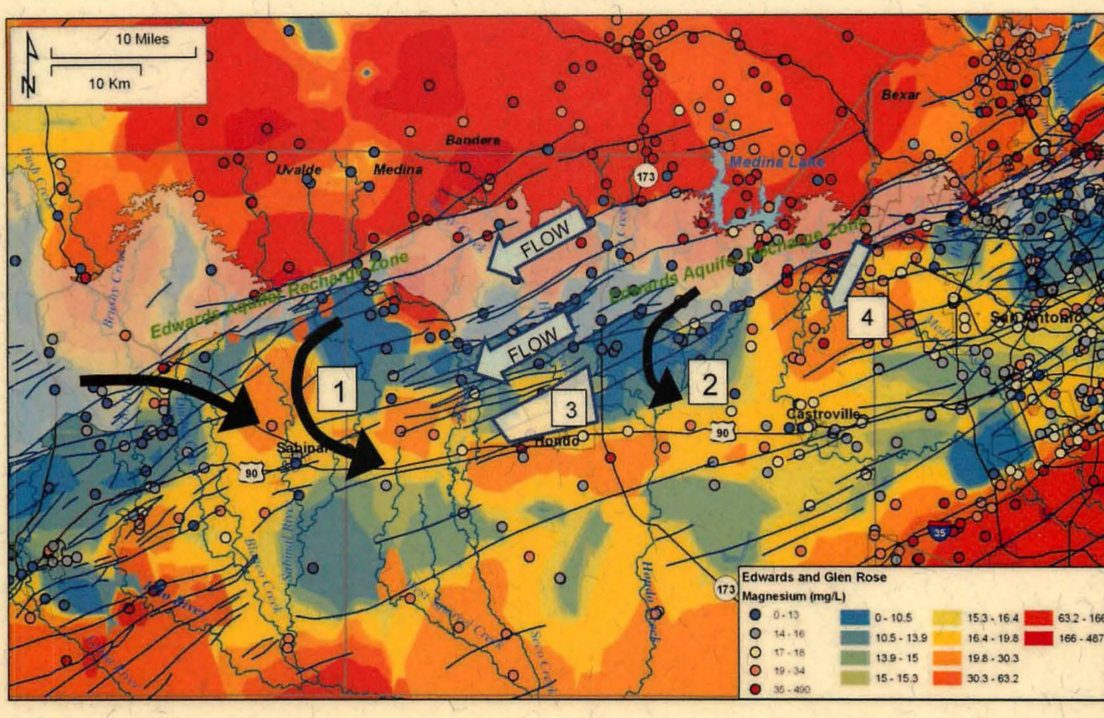
SwRI® Project No. 20-16488

Measuring Floodplain Hydraulics of Seco Creek and Medina River Where They Overlie the Edwards Aquifer

Final Report



Prepared for

Edwards Aquifer Authority

Prepared by

Ronald T. Green, Ph.D, P.G.; F. Paul Bertetti, P.G.; Ronald McGinnis; and James Prikryl

Geosciences and Engineering Division
Southwest Research Institute®

February 2012

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1. INTRODUCTION

Medina County, Texas, hosts significant groundwater resources in a number of alluvial and consolidated rock aquifers. The most significant of these is the Edwards Aquifer, which spans the central portion of the county from its western to eastern boundaries. An estimated 15–25 percent of the recharge of the San Antonio segment of the Edwards Aquifer has been attributed to recharge that occurs in Medina County (Hamilton et al., 2008). Sources of recharge to the Edwards Aquifer typically consist of (i) precipitation on the recharge zone (i.e., autogenic recharge), (ii) surface water focused in river and stream beds (i.e., allogenic recharge) and (iii) as subsurface interformational flow from upstream aquifers. Discharge occurs by spring flow, pumping, and interformational flow to downstream aquifers. To effectively manage the Edwards Aquifer, the water budget must be adequately quantified, and to calculate the water budget within acceptable limits, recharge and discharge of the aquifer must be adequately characterized.

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

This report summarizes the investigation of the hydraulic relationship between Seco Creek and Medina River and the subsurface as it affects the recharge and discharge of the Edwards Aquifer. The Geosciences and Engineering Division of Southwest Research Institute® (SwRI®) performed this project for the Edwards Aquifer Authority. The project considered similar studies of the hydrogeology of Uvalde County performed in the last several years, with particular emphasis on investigations of the hydraulic significance of the Leona, Nueces, Frio, and Dry Frio Rivers and Elm and Turkey Creeks with regard to regional and local aquifers (Green et al., 2006, 2008a,b, 2009a,b). These recent studies were of interest because they provide direct evidence of the hydraulics and the hyporheic exchange of rivers, floodplain sediments, and subsurface flows of these rivers and streams as they cross the Edwards Aquifer. The Edwards Aquifer Authority chose to investigate the Seco Creek and Medina River to better understand the water budget (i.e., sources of recharge and quantities of discharge) in Medina County.

2. TECHNICAL APPROACH

The hydraulic relationships between Seco Creek and Medina River and the Edwards Aquifer were evaluated by (i) characterizing the morphology of the floodplains of Seco Creek and Medina River where they exit the Edwards Aquifer recharge zone; (ii) imaging the subsurface of this floodplain using a geophysical survey; (iii) characterizing the hydraulic properties of the floodplain and the Edwards Aquifer using existing information, a survey of local wells, and a hydrogeological assessment of other relevant information that could contribute to the project; (iv) evaluating water chemistry to discern potential water sources and flow regimes; and (v) assessing the volumetric surface water and groundwater flow in terms of floodplain hydraulics and discharge from the Edwards Aquifer.

3. GEOLOGICAL SETTING

Medina County is served by several regional and local aquifer systems. Geologic structure, depositional environments of the geologic formations, and groundwater elevations define the presence, extent, and hydraulic relationships of these aquifer systems. Aquifers occur in formations from lower Cretaceous limestones (Trinity Aquifer) to Quaternary alluvium (Leona Formation) (Barnes, 1983) (Figure 2). The Edwards Aquifer is the primary aquifer in Medina County. Significant secondary aquifers include the Trinity, Buda Limestone, Austin Chalk, Carrizo-Wilcox, and Leona Formation. Incidental secondary aquifers, those whose extent are limited even on a local scale, include the Escondido Formation and Anacacho Limestone (Figure 3).

3.1. Stratigraphy

The Edwards Aquifer in Medina County is comprised of Lower Cretaceous carbonate (mostly dolomitic limestone) strata (Figure 3). The Edwards Aquifer overlies the (Lower Cretaceous) Glen Rose Limestone, which comprises the lower confining unit of the Edwards Aquifer and is overlain by the (Upper Cretaceous) Del Rio Clay, the basal formation of the upper confining unit. The Buda Limestone and the Austin Chalk are secondary aquifers in Medina County that overlie the Edwards Aquifer. The Upper Cretaceous Anacacho Limestone and Escondido Formation overlie the Austin Chalk in southern Medina County. Upper Cretaceous and (or) Lower Tertiary igneous rocks intrude all stratigraphic units that comprise the Edwards Aquifer. The lower portion of the Carrizo-Wilcox Aquifer, particularly the Wilcox Formation, is present in southern Medina County. Most wells in unconsolidated sediments in Medina County are in the sands and gravels of the Leona Formation and the Uvalde Gravel.

The Edwards Group in Medina County is in the Devils River Trend and San Marcos Platform facies (Figure 2). The Devils River Trend is comprised of a basal nodular unit and the overlying undifferentiated rocks of the Devils River Formation (Clark, 2003). The upper Devils River Formation tends to be the most permeable section in the Devils River Trend facies of the Edwards Aquifer. The lower Devils River Formation is less permeable than the upper section and is typically not a significant source of groundwater (Maclay, 1995; Clark, 2003). The San Marcos Platform in Medina County divided into the Pearson and Kainer Formations.

3.2. Balcones Fault System

The Balcones fault system dominates the geologic structure of Medina County (Figure 4). The Trinity, Edwards, Buda Limestone, and Austin Chalk aquifers are complex karst limestone aquifer systems that have permeability architectures which include a combination of host rock permeability, fractures and fault zones, and dissolution features (Maclay et al., 1981; Maclay and Small, 1983). Displacement along faults of the Balcones fault system has placed the Edwards Aquifer laterally against (side by side with) both older (i.e., Trinity Aquifer in the north) and younger (i.e., Buda Limestone and Austin Chalk) rocks in Medina County. The location and amount of fault juxtaposition are sensitive to the location, geometry, and displacement on faults (Ferrill et al., 2005). The occurrence of and degree to which interaquifer communication occurs are not well defined.

Rocks of the 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, 2003; 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 the hydraulic gradient; in many places it follows tortuous flowpaths controlled by the Balcones fault system. Natural discharge sites for the aquifer include 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) (Figure 4). The arc-shaped zone mostly trends east-northeast and spans much of central Texas. The 16- to 19-mile-wide Balcones fault system has a maximum total displacement of about 1,200 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).

3.3. Igneous Intrusions

There are a limited number of igneous intrusions in southwest Medina County. The presence of igneous intrusions in western Medina County with no surface expression has been inferred using results of an aeromagnetic survey (Smith et al., 2002, 2008) (Figure 5). Magnetic surveys are an effective tool to identify the location and extent of igneous intrusions in Medina County due to the strong magnetic signature of the intrusions relative to the weak magnetic signature of the Cretaceous limestone formations. For this reason, the map of the magnetic field intensity clearly illustrates the location and extent of the igneous intrusions regardless of whether a surface expression of an intrusion is evident (Figure 5). Although the aeromagnetic survey (Smith et al., 2002, 2008) did not cover all of Medina County, the coverage suggests that the extent of the intrusions is limited to the southwestern portion of the county and that water resources in Medina County should not be significantly affected by the limited presence of the intrusions.

3.4. Hydrogeology

Early comprehensive assessments of the geology, hydrology, and water resources of Medina County by the U.S. Geological Survey (i.e., Holt, 1956, 1959; Maclay and Small, 1984; Maclay and Land, 1988; Maclay, 1995) have been augmented with recent focused studies on geologic structure (Small and Clark, 2000; Blome et al., 2004, 2005, 2007; Clark et al., 2006, 2009; Pantea et al., 2008), groundwater flow paths (Clark and Journey, 2006), recharge (Lowry and Couch, 2002; George, 2010; Bradley, 2010, 2011), and water balance (Lambert et al., 2000; Slattery and Miller, 2004; Ockerman, 2005; Pedraza and Ockerman, 2012). A contour map of the potentiometric surface of the Edwards Aquifer representing the EAA 2005 synoptic survey is illustrated in Figure 6 (Hamilton et al., 2006).

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 1950s, the concept of barrier faults that partition the aquifer has become increasingly popular (e.g., Holt, 1956, 1959; Maclay and Small, 1983; Maclay and Land, 1988; Maclay, 1995). It has also been noted that a fault which acts as a barrier to cross-fault flow may 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:

- As both horizontal and vertical flow conduits because fault zones are often preferentially dissolved
- As barriers to flow where displacement is sufficient to juxtapose low permeability media with Edwards limestones
- As both barriers and conduits depending on the nature of the fault

Holt (1956, 1959) first characterized faulting in northern Medina County as a barrier to groundwater flow and characterized the ensuing structures in northern Medina County as flow path features. Holt stated that groundwater flows in solution channels along fractures generally parallel to the fault pattern. Faults with sufficiently large displacements form barriers, diverting groundwater. Water entering the Edwards limestone from the Medina Lake area flows downdip to the south where movement is retarded by the Haby Crossing fault. Most of this groundwater flows to the southwest, along the fault, to the area north of Quihi where the throw is less than the thickness of the Edwards Aquifer. From there, groundwater passes across the fault into the downthrown block to the south.

Holt (1959) noted that the throw of the faults is not sufficient to completely offset the Edwards limestone in the vicinity of Hondo and Verde Creeks and divert groundwater. According to Holt's (1959) characterization, the Medina Lake fault and the fault to its north locally divert the groundwater moving in the outcrop area of the limestone. Faulting between the Medina Lake fault and Hondo does not appreciably affect the southward movement of the groundwater. In the area near Woodard Cave where the Edwards limestone crops out, the faulting is sufficient to affect the movement of the water but does not completely prevent movement across the major fault. The displacement along the fault south of this area is too small to appreciably affect groundwater movement. The Pearson fault and several of the faults southwest of Dunlay may serve as effective barriers to the downdip movement of the Edwards water.

Maclay and Small (1984), Maclay and Land (1988), and Maclay (1995) retained the concept that Balcones fault system in northern Medina County acts as a barrier to flow and that this barrier diverts groundwater flow from northeastern Medina County to southwest Medina County. In this conceptualization, a fault was considered a barrier if the fault displacement equated to 50 percent or greater of the aquifer thickness. Clark and Journey (2006) evaluated geological structural data, hydraulic correlations, and water chemistry to support the conceptualization of faults acting as barriers to flow in Medina County, although the hydraulic and water chemistry data were mostly from the eastern half of the county.

More recently, results from tracer tests in Bexar County demonstrated that faults in the Balcones fault system, at least in Bexar County, do not act as barriers to flow (Johnson et al., 2010). These tracer test results call into question the role of faults as barriers in Medina County. Although the objective of this investigation is not focused on flow path assessment in Medina County, factors that affect discharge from the Edwards Aquifer via stream and river floodplains in Medina County are inextricably linked with the dynamics between the groundwater flow paths and the hydraulics of the floodplain that cross the Edwards Aquifer recharge zone. Therefore, groundwater flow paths are addressed, to the degree necessary, in assessing the role of floodplain discharge from the Edwards Aquifer in Medina County.

4. SURFACE WATER

Surface water flow in Medina County occurs in two principal watersheds: (i) the Seco-Hondo-Quihi Creek basin and (ii) the Medina River basin (Figure 7). Within the Seco-Hondo-Quihi Creek basin, Seco Creek and Parker Creek flow along the west and east flanks of a floodplain that reaches from the southern Edwards Aquifer recharge zone at the north to northern extent of the Carrizo-Wilcox Aquifer recharge zone at the south. The confluence of the two creeks occurs less than 2 miles north of the Carrizo-Wilcox Aquifer recharge zone. Also in this basin, Live Oak, Hondo, Verde, Elm, and Quihi Creeks form a separate sub-basin. All five creeks originate in the Edwards Aquifer recharge zone, eventually forming a single creek approximately 9 miles south of Highway 90 and flowing south to the Carrizo-Wilcox Aquifer recharge zone. To the east, Medina River forms the most significant surface flow feature in the area. The Medina

River flows from Medina Lake and Diversion Lake to the south, then east in southern Medina County where it eventually enters the Carrizo-Wilcox Aquifer recharge zone.

Floodplains of the Seco-Parker Creek system on the west and the Live Oak-Hondo-Verde-Elm-Quihi Creek system on the east coalesce to form a contiguous expanse of Leona Formation sediments (Figure 2). This region spans from Seco Creek on the west to midway between Hondo and Dunway on the east, an east-west distance of approximately 15 miles. The north-south extent of the Leona Formation in central Medina County is also about 15 miles, although the deposits are restricted to the floodplains of Seco, Parker, Live Oak, Hondo, Verde, Elm, and Quihi Creeks in the north and to the floodplains of Seco, Live Oak, and Hondo Creek in the south. Although the surface flow regimes in these floodplains are evident, the extent of subsurface groundwater flow through the floodplains is not. Additional data collection and analysis are needed to form a conceptual model of groundwater flow in the Leona Formation sediments in central Medina County.

Surface-water flow measurements made by the U.S. Geological Survey are available for at the following locations:

- Seco Creek (Site 08201500 at Miller Ranch near Utopia, Site 08202700 at Rowe Ranch near D'Hanis, Site 08202780 at CR 5282 near Yancey),
- Hondo Creek (Site 08200000 near Tarpley, Site 08200020 near Hondo, Site 08200100 at FM 462 near Hondo, Site 08201100 at CR 545 near Yancey, Site 08200720 at SH 173 near Hondo), and
- Medina River (Site 08180015 below Diversion Lake near Rio Medina, and Site 08180700 near Macdona).

Inspection of these potential data sources indicated that the following gauging stations were not active and did not have meaningful databases:

- Site 08202780 at CR 5282 near Yancey on Seco Creek,
- Site 08200020 near Hondo,
- Site 08200100 at FM 462 near Hondo,
- Site 08201100 at CR 545 near Yancey on Hondo Creek, and
- Site 08180015 below Diversion Lake near Rio Medina on Medina River.

Gauging stations with significant measurement datasets are Site 08201500 at Miller Ranch near Utopia, Site 08202700 at Rowe Ranch near D'Hanis on Seco Creek, Site 08200000 near Tarpley, and Site 08200720 at SH 173 near Hondo on Hondo Creek (Figure 7). These gauging stations are the same those the USGS uses to calculate Edwards Aquifer recharge from the Seco Creek and Hondo Creek basins.

Flow in Medina River is perennial and significant. Flow in Seco Creek and other creeks in Medina County is intermittent and typically occurs in response to large precipitation events with a significant surface-flow component.

5. EDWARDS AQUIFER RECHARGE AND DISCHARGE

The Edwards Aquifer Authority documents annual recharge assessments the U.S. Geological Survey made for the major watersheds in the Edwards Aquifer recharge zone (Hamilton et al., 2008). The Edwards Aquifer in Medina County benefits from recharge by two principal watershed basins: (i) the basin located between the Sabinal River basin and the Medina River basin and (ii) the Medina River basin (Figure 7) (LBG-Guyton, 2005).

Total average annual recharge to the San Antonio segment of the Edwards Aquifer for the period 1934-2006 is estimated to be 711,600 acre-ft, of which 174,600 acre-ft, or 25 percent, is attributed to the two principal basins in Medina County (Hamilton et al., 2008). Recharge of the Edwards Aquifer via the two basins is estimated using loss/gain river-flow measurements (Hamilton et al., 2008). Recharge estimates published in Hamilton et al. (2008) assumed that river gauge measurements accurately reflect the amount of water that enters and exits the Edwards Aquifer along reaches of the creeks and rivers that cross the recharge zone. The accuracy of this recharge calculation is also predicated on the assumption that little or no subsurface flow occurs in the floodplains where the creeks and rivers enter and exit the recharge zone. Assessment of subsurface flow in the Leona River floodplain in Uvalde County suggests the subsurface flow component of rivers that cross the Edwards Aquifer recharge zone in Medina County could be significant (Green et al., 2006, 2008a,b). Conversely, similar assessments of the Nueces and Frio River indicated no significant subsurface flow component (Green et al., 2008a, 2009b).

5.1. Analysis of Floodplain Subsurface Flow

The potential for subsurface flow in paleo-stream channels is suggested by the presence of the Leona Formation in the Medina River floodplain and in the outwash plain that contains Seco, Parker, Live Oak, Verde, Hondo, Elm, and Quihi Creeks (Figure 6). The presence and location of paleo-stream channels in the Leona Formation are not easily discerned using existing geologic and hydrogeologic information. The paleo-stream channels, which can act as points of significant discharge from the Edwards Aquifer, however, can be identified and located with the use of near-surface geophysical tools such as electrical resistivity. The potential area for paleo-stream channels in the Leona Formation in the outwash plain in central Medina County spans from Seco Creek on the west to midway between Hondo and Dunway on the east.

5.2. Subsurface Imaging

Electrical resistivity surveys were performed along two transects across Seco and Parker Creeks and one transect across the Medina River to discern the possible presence of high permeability zones characterized by high resistivity that could serve as preferential pathways for groundwater flow (Figure 8). Due to the large number of high-capacity shallow wells in that floodplain north of D'Hanis, the Seco-Parker Creek floodplain was chosen for focused evaluation using an electrical resistivity survey.

The two transects on the Seco-Parker Creek floodplain were chosen to provide a reasonable chance of detecting the presence of paleo-stream channels in the floodplain (Figures 9 and 10). A northern transect was chosen approximately 3 miles north of Highway 90 at a location where the floodplain is relatively narrow and accessible (Figure 9). The northern transect was completed in two segments with a total distance of 1.5 miles. A southern transect on the Seco-Parker Creek floodplain was chosen approximately 4 miles south of Highway 90 and about 2.2 miles north of the confluence of Seco and Parker Creeks (Figure 10). The southern transect was completed in four segments. Multiple segments were required because fencing along property lines prohibited a continuous survey. Three segments were collinearly aligned with a combined distance of 1.1 miles. A 0.5–mile-long fourth segment in the southern transect was located about 1 mile north of the three aligned segments to provide survey coverage of the central portion of the Seco-Parker Creek floodplain. Both Seco-Parker Creek floodplain transects are located within the Edwards Aquifer confined zone. The northern and southern transects are located approximately 5 and 12 miles, respectively, south of the Edwards Aquifer recharge zone.

One electrical resistivity transect was occupied on the Medina River floodplain (Figure 11). The transect was approximately 3.5 miles north of Highway 90 and about 8 miles south of the Edwards Aquifer recharge zone. The transect spanned the width of the Medina River floodplain with the exception of the flooded riverbed on the western flank of the floodplain. The transect was completed in two segments comprising a total distance of 1.6 miles (Figure 11).

The geophysical surveys were conducted using a Syscal ProSwitch electrical resistivity system (Iris Instruments, Orléans, France). The survey system consisted of linear arrays of 72 electrodes spaced 16.4–ft apart. A dipole-dipole electrode configuration array was used. The depth of investigation was approximately 130–150 ft. Measurements along transects requiring more than 72 electrodes were collected using a "roll along" survey method to provide continuous coverage. The measured resistivity data were inverted to provide an interpretation of the subsurface (Loke, 2004).

The resistivity results are graphically illustrated as vertical profiles in Figures 12–19. Results are presented in units of ohm-meters (ohm-m), a measure of the electrical resistivity of the geologic section to an induced current. Modeled electrical resistivity values in the shallow subsurface range from less than 5 to greater than 800 ohm-m in the Medina River transect and the northern Seco Creek transect (Figures 12–13) and from less that 1 to no greater than about 35–50 ohm-m in the southern Seco Creek transect (Figures 14–17).

The two transects on the Seco-Parker Creek floodplain were dramatically different. The northern Seco-Parker Creek floodplain transect indicates significant high electrical resistivity zones (> 500 ohm-m) in the upper 50 ft of the floodplain (Figure 12–13). Resistivity values range up to 800 ohm-m and higher, similar to the resistivity values observed in the Medina River floodplain. The thickness of the high resistivity zones is consistent with the documented thickness of the Leona Formation in Medina County (i.e., 0-65 ft, Holt, 1959).

Conversely, no significant sand and gravel deposits are indicated by the consistently low resistivity values (< 30 ohm-m) in the southern Seco-Parker Creek floodplain transect (Figures 14–17). Deposits in the Seco-Parker Creek floodplain about six miles south of Highway 90 are interpreted to be mostly silts and clays although the upper 30–50 ft appears to be slightly more coarse and permeable than the deeper deposits. The base of the floodplain deposits was not detected at the southern Seco-Parker Creek floodplain transect suggesting the thickness of the deposits is at least 130 ft thick. Given the low electrical resistivity of the deposits, no significant paleo-stream channels were detected in the Seco-Parker Creek floodplain at the southern transect.

The dramatic change in the electrical resistivity survey results between the northern and southern transects of the Seco-Parker Creek floodplain provides compelling evidence of a significant change in the hydraulic capacity of the floodplain. The paleo-stream channel detected in the Seco-Parker Creek floodplain at the northern transect does not appear to continue in the Seco-Parker Creek floodplain to the south of Highway 90.

The Medina River resistivity transect reveals a significant high resistivity layer (> 500 ohm-m) across most of the floodplain (Figures 18–19). The layer is continuous in the upper 50 ft and overlies a low electrical resistivity zone (< 50 ohm-m) that continues to the depth of investigation, approximately 130 ft. The near-surface high electrical resistivity layer is interpreted as the sand and gravel deposits of the Leona Formation. The thickness of the high resistivity zones is consistent with the documented thickness of the Leona Formation in Medina County (i.e., 0-65 ft, Holt, 1959). The underlying low electrical resistivity layer is interpreted as silt and clay fluvial terrace deposits. The base of the floodplain deposits was not detected in the western half of the floodplain. It is possible that the rock units that form the base of the floodplain, thought to be either the Escondido Formation or the Austin Chalk, were detected at the base of the transect in the eastern half of the floodplain.

Logs from six wells near the Medina River transect (TWDB tracking numbers 136386, 273130, 80154, 272495, 273128, and 273134) provide ground truth information used to verify the electrical resistivity survey results (Table 1) (Figure 11). The top and bottom of the Leona Formation are converted to absolute elevation (ft, msl) for comparison. As indicated by the well log information, the formation has uniform thickness of about 7 ft and is relatively level, which is consistent with results from the electrical survey. The well logs allow for correlating high resistivity with the sand and gravel deposits of the Leona Formation. The Leona Formation spans a width of about 6,000 ft from 1,000 ft to 7,000 ft across the Medina River transect. The base of the formation is about 30–35 ft below ground elevation.

Table 1. Borehole information for wells located proximal to the Medina River electrical resistivity survey transect. Data are from the Texas Water Development Board website.

Well ID Number	Ground Elevation (ft, msl)	Thickness of Leona Formation (ft)	Depth to Top of Leona Formation (ft)	Depth to Bottom of Leona Formation (ft)	Elevation of Top of Leona Formation (ft, msl)	Elevation of Bottom of Leona Formation (ft, msl)
136386	794	4	24	28	770	766
273130	790	7	28	35	762	755
80154	795	7	19	26	774	769
272495	829	7	44	51	785	778
273128	830	7	54	61	776	769
273134	795	5	23	28	772	767

6. WATER CHEMISTRY

Hydrochemical data, when combined with hydrologic information, can provide important independent and supportive evidence for a hydrological conceptual model. Collection and analysis of water chemistry data may be keys to identifying groundwater flowpaths and extremely valuable in discerning groundwater differences in hydrogeology investigations of the Edwards and secondary aquifers in Kinney and Uvalde Counties (Green et al., 2006, 2009a) and of the Carrizo-Wilcox Aquifer in the Wintergarden Region (Green et al., 2008a). In this report, historical analyses of water quality were used to evaluate the hydraulic interactions in the floodplains near Seco Creek and the Medina River within Medina County and to evaluate the potential flowpaths and connections between the Trinity, Edwards, and Carrizo-Wilcox Aquifers.

Although this study focused on Medina County, the geochemical assessment boundaries were extended to include the natural limits of the hydrologic system. In this case, in addition to Medina County, data were assembled for all aquifers within Uvalde, Bandera, Zavala, Frio, Atascosa, and Bexar Counties. A focus was placed on the Trinity, Edwards, Carrizo-Wilcox, and Leona Formation Aquifers, but evaluation also included the Austin Chalk, Anacacho Limestone, and Escondido Formation Aquifers.

The Texas Water Development Board (TWDB) groundwater database provided well location, well information, and hydrochemical data for wells. Of the wells analyzed, water-quality data were available for about 1,500 wells, which represented a total of about 6,350 water-quality samples (many wells were sampled more than once). The water-quality data in the database represent a summary of data collected over several decades. In general, the most recent analytical data available for each well were used. Exceptions included samples that showed cation-anion imbalance of greater than 10 percent or that were missing values for key chemical constituents, such as calcium.

The hydrochemical data are summarized in several formats in this report to depict chemical trends (e.g., hydrochemical contour maps). Equilibrium modeling using PHREEQCi v.2.15 (Parkhurst and Appelo, 1999) and statistical analyses (ArcGIS v.10 and Aquachem v.2011.1) were also used to further identify geochemical trends and potential flow path interactions.

Previous hydrochemical studies in Medina County have been primarily associated with general background studies to delineate flowpaths in the Edwards Aquifer. Holt (1956, 1959) provided an initial summary of water quality in Medina County, including a review of characteristics from the Trinity, Edwards, Carrizo-Wilcox, and other aquifers. Holt (1956) noted the nitrate contamination of several Leona Formation wells—a condition observed again in samples collected in 1992. The relatively poor water quality of Indio/Wilcox and Escondido wells was evident in the analyses. Holt (1956) suggested that some of the poor water quality may be a result of contamination from petroleum exploration activities.

Pearson and Rettman (1976) conducted a comprehensive geochemical sampling of Edwards Aquifer waters across south-central Texas, including those of Medina County. These samples included stable isotope, carbon-14, and tritium analyses that would be used in subsequent analyses to develop conceptual models of flowpaths in the Edwards Aquifer (Maclay and Small, 1983; Buszka, 1987; Maclay and Land, 1988; Maclay, 1995; Groschen, 1996; Clark and Journey, 2006). As part of its annual survey of water quality, the EAA has collected water chemistry samples from Edwards Aquifer wells in Medina County for a number of years (e.g., Hamilton et al., 2008). These data have generally been incorporated into the TWDB database and are included in this evaluation.

6.1. Leona Formation Analyses

A trilinear plot of water chemistry from Edwards, Trinity, and Leona Formation wells is shown in Figure 20. With few exceptions, the water chemistry of the Leona Formation is dissimilar to fresh water from both the Edwards and Trinity Aquifers. As noted in previous studies (e.g., Green et al., 2006), fresh-water Trinity Aquifer chemistry is quite similar to that of the Edwards Aquifer, but sodium and potassium generally contribute less to the cation content of Trinity Aquifer waters (Figure 20). Two saline-water trends, one composed of calcium and sulfate and the other composed of sodium and chloride, are also evident (Figure 20). Both saline-water trends appear in data from the Medina County region because of the transition in saline-water facies along the southern boundary of Uvalde and Medina Counties (Oetting et al., 1996).

A map of Leona Formation, Edwards Aquifer, Escondido Formation, and Austin Chalk wells with available water chemistry analyses is shown in Figure 21. As Holt (1956) previously noted, chloride concentration data (Figure 21) indicate that the quality of water in the Austin Chalk and Escondido Formation is generally poor relative to the Edwards Aquifer. Chloride concentrations measured in Leona Formation wells vary by location. The cluster of wells (sampled in 1992) near the intersection of Seco Creek and Highway 90 indicates a degradation in water quality from north to south in that area.

Sulfate concentrations in those wells show a similar trend of lower water quality toward the south (Figure 22).

The number of Leona Formation wells that have available water chemistry analyses is quite low relative to the total number of Leona Formation wells in the TWDB database. Consequently, the concentration of sampled wells in the Seco Creek area is not spatially representative of the Leona Formation wells in Medina County (Figure 22). Unfortunately, the water chemistry is quite varied in these other Leona Formation wells and no substantive inferences can be drawn regarding potential flowpaths or sources of waters in the Leona Formation to the east near Hondo Creek or near the Medina River. Additional sampling is warranted if the potential for flow in the Leona Formation gravels along the Medina River is to be validated using hydrochemistry.
The change in water quality of Leona Formation wells near Seco Creek and Highway 90 is similar to the trend observed for the waterholes along the Frio River in Uvalde County (Green et al., 2009b). For the Leona Formation wells, the total dissolved solids (TDS) content, along with concentrations of all major cations and anions, increases over a distance of about 6 miles. Also, like three of four Frio River waterholes, modeling of these well waters indicates they are not in equilibrium with atmospheric CO_2 (g). The wells also exhibit high concentrations of nitrates (Figure 23), a condition that Holt (1956) previously noted.

The transition from fresh to relatively saline water for Leona Formation wells in this area is depicted in Figure 24. Wells 69-38-907 (north), 69-46-610 (intermediate), and 69-46-604 (south) are highlighted in Figure 24 (and Figure 20) and are located along a path from north to south. Increases in sodium and chloride are evident and fall generally along a 1:1 line, indicative of evaporative effects (or halite dissolution, which is discounted due to the lack of halite in the Leona Formation). The variation in chemistry for these Leona Formation wells is not the result of upward leakage from the Edwards Aquifer. Not only is the potentiometric surface of the Edwards Aquifer too low in this region (see Section 7), but the Edwards Aquifer is characterized by low chloride and sulfate concentrations throughout this area.

There is no chemical transition within the Edwards Aquifer in central Medina County equivalent to the transition that occurs along the Frio River reach in Uvalde County where the waterholes are located. Moreover, geochemical modeling indicates contributions from mixing of more saline Edwards Aquifer waters only satisfies part of the increase in concentrations of these Leona Formation waters. The increased TDS content may be the result of evaporative concentration of dissolved constituents, which was a significant contributor to the Frio River waterhole evolution, but disequilibrium in CO_2 (g) suggests poor communication with the atmosphere. Dissolved constituent concentration increases are most likely due to evaporation of recharge waters that infiltrate over time into a relatively stagnant flow system. Increases in CO_2 (g) are caused by high soil CO_2 (g) activities. Additional increases in major ions are contributed by partial dissolution of calcite, gypsum, and silica in the Leona Formation sediments.

This concept of localized, concentrated recharge is also supported by elevated nitrate levels. Overall, water quality of the Leona Formation in this area suggests a zone of low and intermittent flow in which recharge is dominated by infiltration of runoff impacted by evaporation. This would seem to preclude the southern Seco Creek as being a significant conveyance of groundwater to the south.

6.2. Edwards Aquifer Flowpath Analyses

Maclay (1995) summarized many years of geologic, hydrologic, structural, and geochemical data from the Edwards Aquifer region to postulate a general conceptual model of flowpaths in Medina County (Figure 25). The flow model of Maclay and Land (1988), constructed using much of the data later summarized in Maclay (1995), produced flow vectors in Medina County that indicated major east to west flow within the recharge zone from the northeast and central portions of the county to the western boundary prior to turning south and east to flow across the lower portion of the county within the confined zone. A second flow path originated near Medina Lake in the north and flowed southwest before turning east between Hondo and Castroville (Figure 25).

Groschen (1996) refined these flow paths using tritium and other geochemical data, supported by structural and hydraulic data. In particular, Groschen (1996) defined a flowpath (Western Medina Flowpath) originating in the recharge zone of north-central Medina County that flows southwest, constrained by faults, to the Medina-Uvalde County boundary and the city of Sabinal where it turns east and flows back across south-central Medina County (Figure 25). Groschen (1996) did not describe potential flowpaths originating from the south of Medina Lake, but he did describe stable isotope data from the lake and two Edwards Aquifer wells to the south that indicate the aquifer is receiving recharge from a mixture of lake leakage and precipitation in this region. When coupled with the proposed Western Medina Flowpath, this would result in flowpaths generally consistent with the model flow vectors shown in Maclay (1995).

Fahlquist and Ardis (2004) summarized U.S. Geological Survey geochemical sampling of Trinity and Edwards Aquifer wells sampled in the late 1990s. Included in the Fahlquist and Ardis (2004) report were results from tritium samples collected from both the Trinity and Edwards Aquifers in the Medina County region. These results were generally consistent with data Groschen (1996) provided and indicated much of the Edwards Aquifer waters in Medina County were young (5–10 yrs since recharge). Exceptions to the generally young water age included waters from two Edwards Aquifer wells located just north of Hondo Creek in central Medina County (Falhquist and Ardis, 2004). Tritium data reported in Groschen (1996) also indicated older waters in the same area north of Hondo Creek.

More recent work by Clark and Journey (2006) used geochemical, structural, and groundwater and surface water hydraulic data to further refine Edwards Aquifer flowpaths in northern Medina County. Clark and Journey (2006) proposed that four distinct flowpaths can be identified, all of which originate along the Edwards Aquifer recharge zone in northeast and north-central Medina County and flow to the west along fault trends until turning southward and eastward in the west-central portion of the county (and west of Hondo) (Figure 25).

A detailed examination of the potential flowpaths in Medina County is beyond the scope of this study; however, using the hydrochemistry data provided in the TWDB database, several observations can be made. Water chemistry data from the Trinity and Edwards Aquifers in the Medina County region are plotted in Figures 26–29. The figures depict concentrations of analytes at individual wells, as well as geostatistical (contour) maps of concentrations for the region. To generate the contour maps, Trinity and Edwards Aquifer data were combined and an inverse distance weighting (IDW) method was used to interpolate concentration values between neighboring wells. The IDW interpolations were not constrained by the presence of faults or other geologic structures. In later analyses (Figures 28–29), chemical concentration contours were conditioned using the fault locations as barriers and the data were interpolated using a kernel smoothing. As noted in Section 3, faults in the Edwards Aquifer may or may not act as barriers to flow depending on the specific geometry of the faults and the nature of flow in the vicinity of the faults.

In general, the concentration and prediction maps clearly delineate the Trinity and Edwards Aquifers and provide support for east to west flowpaths in northern Medina County along fault lines as others proposed (Maclay, 1995; Groschen, 1996; Clark and Journey, 2006). Maps of chloride and sulfate concentrations (Figures 26 and 27, respectively) show the significant input of dilute water along the central and western portions of the Edwards Aquifer recharge zone in Medina County. Even without including the presence of faults as potential barriers to flow, Figures 26 and 27 show the heavy influence of Trinity Aquifer chemistry in the northern part of the county and are consistent with the Western Medina Flowpath Groschen (1996) proposed.

Chloride and sulfate data also suggest the presence of dilute flow into the Edwards Aquifer confined zone along the Seco Creek trace and near Elm and Quihi Creeks between Hondo and Castroville (Figures 26–27). Chloride and sulfate data also indicate an isolated zone of higher concentration waters just north of the city of Hondo, near Hondo Creek. These regions of varying concentrations are consistent with flowpaths Maclay (1995) proposed and with data from Groschen (1996).

It is likely that faults do play a role in the actual paths for some water flow within the Edwards Aquifer in Medina County. Figures 28 and 29 depict chloride and magnesium concentration data and contour map predictions that are conditioned using all faults as barriers to flow. With the barrier effect added, the chloride and magnesium maps highlight compartmentalization of the aquifer along fault lines, and the maps remain quite consistent with patterns predicted by proposed east to west flowpaths in the north that turn south and east near Sabinal. Adding the barriers does not eliminate the observed plume of more dilute water in the confined zone between Hondo and Castroville. All of the maps (Figures 26–29) indicate a zone of mixed Edwards and Trinity Aquifer water southwest of Medina Lake near the northeast Medina-Bexar County boundary (see area labeled 4 in Figure 30).

Figure 30 provides a summary of flowpaths suggested by the hydrochemical data analyses in this report:

- The data are consistent with at least two flowpaths in northern Medina County that flow westward into the confined zone before turning south and eastward near the Medina-Uvalde County boundary and the city of Sabinal, where they mix with eastward flow from Uvalde County. These flowpaths are similar to those proposed by Maclay (1995), Groschen (1996), and Clark and Journey (2006) (Figure 25).

- The data appear to indicate a shorter flowpath along the southern part of the recharge zone that turns south and eastward between Hondo and Castroville near the Elm-Quihi-Hondo Creek confluence. This flowpath is consistent with the model flowpath of Maclay (1995) and data in Groschen (1996), but may not be consistent with the south-central flow path Clark and Journey (2006) proposed. Clark and Journey's (2006) proposed turning point of the south-central flowpath is not constrained by data (all of their wells are upstream), however the upstream portion of their flowpath is consistent with data in Figures 25-30;

- The data indicate an isolated block of higher TDS water just north of Hondo. This isolated block is consistent with data from Groschen (1996) and Fahlquist and Ardis (2004).

- The data indicate a zone of Trinity and Edwards Aquifer mixing west and southwest of Medina Lake near the Medina-Bexar County boundary. These data appear to be consistent with data from Clark and Journey (2006), but are not consistent with their proposed flow path for that area.

Although the analyses presented here are qualitative, they take into account water chemistry data from a large number of wells in both the Trinity and Edwards Aquifers. The analyses clearly delineate differences in the aquifer chemistries and known locations of the Edwards Aquifer saline zone.

6.3. Interaction of Edwards and Carrizo-Wilcox Aquifers

One conclusion of Green et al. (2008a) was that recharge of the Carrizo-Wilcox Aquifer in northern Zavala County was heavily influenced by focused recharge from the Nueces River and underground flow in paleo-gravel channels of the Leona Formation in the Leona River floodplain. One indication of that recharge was the Edwards Aquifer-like chemical signature of waters in the Carrizo-Wilcox Aquifer in northern Zavala County. Figure 31 shows a map of calcium concentrations of the Edwards and Carrizo-Wilcox Aquifers in Medina and Frio Counties. The magnitude and range of calcium concentrations pertaining to each color of the contour plots is similar for both aquifers. Noteworthy is the relatively high calcium concentration plume within the Carrizo-Wilcox

Aquifer in northern Zavala and Frio Counties. The eastern extent of this plume is approximately where Hondo Creek crosses the Carrizo-Wilcox recharge zone.

The high-calcium plume in central Medina County is not present to the east in Atascosa County or to the west in western Zavala County (Figure 31). The magnitude of the concentrations of calcium in the Carrizo-Wilcox Aquifer suggests that some evaporative concentration has occurred prior to recharge. One hypothesis for the existence of this plume is that focused recharge to the Carrizo-Wilcox Aquifer from streams and/or underground conveyances of Edwards Aquifer-like water has produced this plume, and, in effect, the plume represents a different recharge mechanism that is not associated with distributed recharge from precipitation for the Carrizo-Wilcox in this region. Plots of other chemical constituents, such as bicarbonate and magnesium (not shown), reveal similar chemical distribution patterns and are also consistent with an Edwards Aquifer-like source. Although current conveyances of Edwards Aquifer waters exist, such as the Nueces River and Leona Formation in Uvalde County and, potentially, Hondo Creek in Medina County, the timing and magnitude of this proposed recharge source is unknown. Additional study is required before conclusions can be drawn, but the data indicate potential loss of Edwards Aquifer water to the Carrizo-Wilcox Aquifer in this region.

7. SUBSURFACE FLOW CHANNELS IN MEDINA COUNTY

Evidence examined during this investigation is used to ascertain the presence of subsurface flow associated with paleo-stream channels in central Medina County. A hypothesized map of paleo-stream channels was formulated using well data. The conceptual model was constrained by the known framework of the geologic structure. Subsurface imaging based on an electrical survey allowed for vetting of assumptions on which the conceptual model was formulated. Lastly, water chemistry analysis indicated whether the flow paths were consistent with water chemistries.

7.1. Well Hydraulics

Water-well information for central Medina County was compiled and evaluated as a surrogate for hydraulic testing data. Although quantitative hydraulic property assessment is not advisable using standard well information, such as depth and pumping capacity, the presence or absence of high-capacity wells can indicate the locations of prolific paleo-stream channel deposits. For example, high-capacity irrigation pivots require a minimum of 500 gpm and preferably 1,000 gpm wells for sustainable operation. Wells with limited depths (i.e., less than 60–70 ft) in the river floodplains in central Medina County can only provide the desired capacity for pivot irrigation if they tap into a prolific sand and gravel paleo-stream channel. The presence of high-capacity irrigation wells in the Leona Formation in central Medina County is reasonable evidence of the presence of paleo-stream channels.

The absence of high-capacity irrigation wells in the Leona Formation, however, is not conclusive proof that paleo-stream channels are absent in the Leona Formation, although decades of well drilling in this area without encountering paleo-stream channels is a good indication that significant paleo-stream channels are not present. Thus, the absence of high-capacity irrigation wells in specific areas in central Medina County floodplains is suggestive, but not conclusive, evidence that paleo-stream channels are not present at those locations. Conclusive assessment on the presence or absence of paleo-stream channels requires corroborating evidence in addition to water-well information.

Well depth data for central Medina County are plotted in Figure 8. Wells denoted with red dots have depths less than 75 ft, which is approximately equal to the maximum depth of the Leona Formation (i.e., 65 ft, Holt, 1959). As illustrated, shallow wells are generally restricted to the Leona Formation in the creek and river floodplains in central Medina County. Wells in central Medina County are also plotted according to the formation into which they are completed (Figure 32). The formations of the plotted wells are Leona Formation, Uvalde Gravel, Reklaw Formation, Escondido Formation, Anacacho Formation, and Austin Chalk. Edwards Aquifer. The northern extent of Leona Formation wells begins abruptly along a line that traverses the three floodplains that extend north into the Edwards Aquifer recharge zone: Seco-Parker Creek, Hondo Creek, and Verde Creek (Figure 8). Note that this line is coincident with the southern extent of the surface exposure or recharge zone of the Austin Chalk.

7.2. Paleo-Stream Channel Hydraulics

This investigation focused on paleo-stream discharge in the Seco Creek and Medina River floodplains. This information provides a basis to estimate paleo-stream discharge over a larger geographical area considering geologic structure and hydrostratigraphic information. Using this information, the paleo-stream channel hydraulics were evaluated for the geographical area that spanned from the eastern boundary of the Frio River floodplain located south of Uvalde to the west to the eastern boundary of the Medina River floodplain to the east. This expanse is categorized in four separate compartments for discussion purposes: two have significant underflow via paleo-stream channels and two do not. As will be discussed, the region between the Frio River floodplain to the west and the Seco-Parker Creek floodplain to the east and the region between the Hondo Creek floodplain on the west and the Medina River floodplain on the east are not believed to exhibit meaningful underflow via paleo-stream channels. Conversely, the Hondo Creek floodplain with its contributing tributaries and the Medina River floodplain are believed to exhibit meaningful underflow via paleo-stream channels. Following are discussions of the four compartments from west to east.

7.2.1. Area Between Frio River Floodplain and Leona Formation in Central Medina County

There is an absence of Leona Formation wells in the region between the Frio River floodplain to the west and the Seco-Parker Creek floodplain to the east and downgradient from where the Cretaceous-age rocks crop out. The downdip boundary of the Edwards Aquifer recharge zone is aligned with Seco Creek on the east and the Uvalde salient on the west of this region (Figure 4). The combined effect of these two features has elevated the base of the Leona Formation where it abuts the southern extent of the Austin Chalk recharge zone (Figure 8). The elevation of the downdip boundary of the Austin Chalk recharge zone is approximately 1,050 ft msl at the Uvalde-Medina County line. The base of the Leona Formation, with a maximum thickness of 65 ft, is approximately 985 ft msl where it abuts the Austin Chalk. The Edwards Aquifer groundwater elevation in this area, however, is less than 850 ft msl (Green et al., 2006); thus the elevation of Edwards Aquifer groundwater in eastern Uvalde County and western Medina County (i.e., west of Seco Creek) is too low to discharge to the Leona Formation.

An evaluation of secondary aquifers in Uvalde County concluded that the Austin Chalk and Buda Limestone are essentially unsaturated in eastern Uvalde County (Green et al., 2009a). Therefore, there is no opportunity for the Austin Chalk to recharge paleo-stream channels in eastern Uvalde County if there are any channels in this area. In summary, the presence or absence of paleo-stream channels in eastern Uvalde County is inconsequential to water budget analysis because significant quantities of water are not being transported or discharged from aquifers in this area.

7.2.2. Leona Formation in Central Medina County

Paleo-stream channels in the Leona Formation located in central Medina County are interpreted to originate in the floodplains of Seco, Parker, Live Oak, Hondo, Verde, Elm, and Quihi Creeks. Geophysical and water chemistry evidence suggests that the paleo-stream channel in the Seco-Parker Creek floodplain north of Highway 90 turns east near Highway 90 and eventually flows to the southeast in the large outwash plain located south of Hondo. There is no indication of a paleo-stream channel in the Seco-Parker Creek floodplain to the south of Highway 90.

A number of minor tributaries coalesce with Live Oak Creek to the west and south of Hondo. Verde, Elm, and Quihi Creeks coalesce with Hondo Creek east of Hondo and north of Highway 90. Live Oak Creek eventually coalesces with Hondo Creek about 9 miles south of Highway 90. The paleo-stream channels for these creeks are believed to coalesce into a single downstream channel that aligns with Hondo Creek to the south.

Shallow wells align closely with these creeks near their ancestral springs to the north of Highway 90, but are spread over a wider area at downstream locations. Specific locations of paleo-stream channels south of Highway 90 are not known at this time. It is possible that the paleo-stream channels differ from the current creek locations. For example, the limited number of Leona Formation wells in the Hondo Creek floodplain south of Highway 90 could be interpreted as evidence that the paleo-stream channels for Hondo, Elm, and Quihi Creeks align more closely with Live Oak Creek and its tributaries and not the current Hondo Creek.

Ancestral headwater locations of the paleo-stream channels are interpreted to be located at the southern extent of the Austin Chalk surface exposure. This interpretation is based on the coincident alignment of the downdip boundary of the Austin Chalk and the most updip occurrence of wells located in the paleo-stream channel (Figure 8). If this interpretation is valid, the paleo-stream channels are recharged directly from the Austin Chalk. Aerial exposure of the ancestral springs likely ceased in the late Pleistocene, after which subsequent alluviation buried the springs and paleo-stream channels with 40–50 ft of sediments resulting in the current state of the floodplain (Doyle, 2003).

Elevations of the ancestral springs that discharge to the paleo-stream channels in Seco, Parker, Live Oak, Hondo, Verde, Elm, and Quihi Creeks were calculated by subtracting 65 ft (the maximum thickness of the Leona Formation) from the surface elevation of the creek beds at the estimated southern extent of the Austin Chalk recharge zone (Table 2). These estimates are approximate and could be refined with controlled borehole information, but elevations of the seven ancestral springs are consistent with values varying from 835 to 890 ft msl. The elevation estimates are believed to be conservatively low and could be higher if the Leona Formation thickness is less than 65 ft.

Table 2. Comparison of base elevation of ancestral springs and groundwater elevations of nearby Edwards Aquifer wells using the July 1999 synoptic survey measurements (Hamilton et al., 2004). The ancestral spring is set at the base elevation of the Leona Formation.

Creek	Ground Elevation (ft, msl)	Base Elevation of Leona Formation (ft, msl)	Closest EAA Monitoring Well	Edwards Aquifer Groundwater Elevation (ft, msl)
Seco	920	855	69-38-902	778.30
Parker	935	870	69-38-906	783.18
Live Oak	955	890	69-39-801	767.97
Hondo	945	880	69-39-901	700.93
Verde	900	835	69-40-403	793.85
Elm	900	835	69-40-901	723.91
Quihi	945	880	68-33-102	845.83

The groundwater elevation in the Austin Chalk at the locations of the ancestral springs has to be at least as high as the base elevation of the Leona Formation at the locations of the ancestral springs if the paleo-stream channels are to be recharged by the Austin Chalk. Edwards Aquifer groundwater elevations near the ancestral springs were estimated using results from the EAA 1999 groundwater elevation synoptic survey (Hamilton et al., 2006). As presented in Table 2 and illustrated in Figure 6, the elevation of groundwater in the Edwards Aquifer is significantly and consistently lower than the elevation of the ancestral springs.

This difference in elevations confirms that the ancestral springs and the paleo-stream channels in central Medina County are not in direct hydraulic communication with the Edwards Aquifer. Similarly, by extension, the Austin Chalk is not in direct hydraulic communication with the Edwards Aquifer in central Medina County. Fault displacement or fault shear between the Edwards Aquifer and the Austin Chalk is apparently sufficiently large to preclude direct hydraulic communication between the Edwards Aquifer and the Austin Chalk. It is possible, if not likely, however, that the Austin Chalk is recharged with Edwards Aquifer water albeit via an indirect path of recharge. Groundwater flow paths that recharge the Austin Chalk are not easily discerned at this time. The flow paths upgradient of the Austin Chalk could abide by the flow paths that Holt (1956, 1959) and others hypothesized, in which case flow would be from the west.

The large number of Leona Formation irrigation wells in the floodplain south of Hondo indicates that paleo-stream channels in that region are sufficiently recharged to sustain high capacity pumping needed for irrigation. Groundwater that flows downstream from the outwash plain via the central Medina County paleo-stream channels eventually arrives at the recharge zone for the Carrizo-Wilcox Aquifer. The northern boundary of the Wilcox Formation is slightly north of the confluence of Live Oak Creek and Hondo Creek or about 8 miles south of Highway 90. Because of the absence of the high-capacity shallow wells from this point south, groundwater flow in the paleo-stream channels in the north is believed to have either discharged into the creeks or recharged the Carrizo-Wilcox Aquifer.

Insufficient information is available to characterize the Leona Formation paleo-stream channels in central Medina County. Without this characterization, it is difficult to accurately estimate the volume of water transported via the Leona Formation paleo-stream channels in central Medina County.

7.2.3. Area Between Leona Formation in Central Medina County and the Medina River Floodplain

Inspection of the geologic map of Medina County (Figure 2) indicates the absence of river floodplains and Leona Formation sediments in the area between the Leona Formation in central Medina County and the Medina River floodplain with the exception of Chacon Creek in the western portion of this area. Limited information on Chacon Creek is available, however, its floodplain is limited in size, both in width and length. It appears to be a sub-basin that originates south of the Medina River floodplain. There are only about five known Leona Formation wells in the sub-basin, and the well capacities are not known. The small size of the Chacon Creek floodplain and the limited number of Leona Formation wells suggest that paleo-stream channels, if present in the floodplain, would not have significant capacity for underflow. There are virtually no other Leona Formation deposits mapped between the floodplains of Chacon Creek and Medina River. In the absence of Leona Formation sediments, there is no prospect for paleo-stream channels to have formed in the area between the Leona Formation in central Medina County and the Medina River floodplain.

7.2.4. Medina River Floodplain

The Medina River paleo-stream channel appears to track the Medina River floodplain from Diversion Lake to where it enters Bexar County. It is not known whether or where the Leona Formation paleo-stream channel in the Medina River floodplain is in hydraulic communication with the Medina River. Additional field, geologic, and hydraulic information is needed to make this determination.

Because of its pervasive extent, the high electrical resistivity zone in the Medina River transect is interpreted as a high-energy outwash deposit comprised mostly of sands and gravels. It likely has high capacity for subsurface groundwater flow. Geophysical survey results from the Medina River floodplain and a previous hydraulic assessment of the Leona Formation in the Leona River floodplain provide a basis on which the hydraulic capacity of the paleo-stream channel in the Medina River floodplain can be estimated (Green et al., 2008b). The total groundwater discharge, Q, is calculated using Darcy's Law (Freeze and Cherry, 1979)

$$Q = AK\nabla h$$

where A is the cross-sectional area, K is the hydraulic conductivity, and ∇h is the hydraulic gradient of the Leona Aquifer at the study site.

The paleo-stream channel in the Medina River floodplain is estimated to be 6,000 ft wide and 7 ft thick for a cross-sectional area of 42,000 ft^2. The gradient of the paleo-stream channel is assumed to be consistent with the gradient of the current Medina River or 0.0025 ft/ft. This gradient is also consistent with the measured hydraulic gradient of the Leona River floodplain paleo-stream channel (Green et al., 2009b). The hydraulic properties of the Leona Formation in the Medina River floodplain have not been measured with an aquifer test and are estimated using documented values for a coarse gravel (i.e., 20,000–200,000 ft/d, Bear, 1972; Freeze and Cherry, 1979). This equates to approximately 24-240 cfs or 17,500–175,000 acre-ft/year of flow through the Medina River floodplain paleo-stream channel deposits. If an average permeability of 100,000 ft/d is assumed for the Leona Formation deposits, underflow would be 120 cfs or 88,000 acre-ft/year in the Medina River floodplain.

The average Medina River surface discharge is 202 cfs or 146,000 acre-ft/year for the period 1981-2011 (U.S. Geological Survey website measured at station 08180700 near Macdona, Texas). Based on this assessment, discharge as underflow could be comparable to surface flow in the Medina River floodplain. If average values are assumed, total flow via the Medina River floodplain is approximately 322 cfs (~234,000 acre-ft/yr). Underflow in the paleo-stream channel in the Medina River floodplain accounts for approximately 38 percent of the total average discharge via the Medina River floodplain

Note that the average annual Medina River discharge varied from a low of 38.1 cfs in 2009 to as high as 953.7 cfs in 1992, a factor of 25 difference in rates. It is likely that the paleo-channel underflow also varies with time; however, insufficient data are available to ascertain this variance. The paleo-stream channel rate of 120 cfs (88,000 acre-ft/year) is believed representative of average conditions, and year-to-year variances could be considerable.

8. CONCLUSIONS

Effective management of the Edwards Aquifer requires that its water budget be accurately known. Central to calculation of the water budget of the Edwards Aquifer are recharge and discharge distributions and rates. Current estimates of recharge of the Edwards Aquifer by the Seco and Hondo Creeks and Medina River (i.e., annual medium of 174,600 acre-ft) are predicated on the assumption that underflow in the Seco and Hondo Creeks and Medina River floodplains is negligible and that recharge from these rivers is accurately measured using river flow gauges.

This investigation was undertaken to improve understanding of the hydraulic importance of the Seco Creek and Medina River to the Edwards Aquifer and to evaluate whether this conceptualization of recharge by these rivers is valid. As a secondary objective, hydrogeological and water chemistry data were examined to ascertain the nature of groundwater flow paths in the Edwards Aquifer in Medina County.

In general, the hydrochemical analyses conducted in this study provide support for east to west flowpaths in northern Medina County along fault lines previous investigators proposed (Maclay, 1995; Groschen, 1996; Clark and Journey, 2006). These flowpaths are evaluated both with faults as barriers to flow and with faults not acting as barriers; however, it is likely that faults do play a role in the actual paths for flow within the Edwards Aquifer in Medina County. With the barrier effect added, the chloride and magnesium maps highlight compartmentalization of the aquifer along fault lines, and the maps remain quite consistent with patterns predicted by proposed east to west flowpaths in the north that turn south and east near Sabinal. Adding the barriers does not eliminate the observed plume of more dilute water in the confined zone between Hondo and Castroville.

Hydrochemical data analyses also indicate at least two flowpaths in northern Medina County that flow westward into the confined zone before turning south and eastward near the Medina-Uvalde County boundary and the city of Sabinal, where they mix with eastward flow from Uvalde County. These flowpaths are similar to those Maclay (1995), Groschen (1996), and Clark and Journey (2006) proposed. The data appear to indicate a shorter flowpath along the southern part of the recharge zone that turns south and eastward between Hondo and Castroville near the Elm-Quihi-Hondo Creek confluence. This flowpath is consistent with the model flowpath of Maclay (1995) and data in Groschen (1996), but may not be consistent with the south-central flow path Clark and Journey (2006) proposed. The data indicate an isolated block of higher TDS water just north of Hondo. This isolated block is consistent with data from Groschen (1996) and Fahlquist and Ardis (2004). Hydrochemical data indicate a zone of Trinity and Edwards Aquifer mixing west and southwest of Medina Lake near the Medina-Bexar County boundary. These data appear to be consistent with data from Clark and Journey (2006), but are not consistent with their proposed flow path for that area.

Data for the Carrizo-Wilcox Aquifer suggest some recharge connection to an Edwards Aquifer-like source, but more study is required to draw any conclusion regarding the interaction between the Edwards and Carrizo-Wilcox Aquifers south of Medina County. When combined with the hydrostratigraphic framework of the area, water chemistry, hydraulics, and subsurface imaging can provide the basis to develop a conceptual model of the hydraulic boundary at the southern edge of the Edwards Aquifer recharge zone in central Medina County.

Geologic structure, subsurface imaging, groundwater and surface-water elevations, and water quality of the Leona Formation sediments in central Medina County and the Medina River were examined to evaluate the hydraulic relationships between the Leona Formation sediments and Medina River floodplain systems and the Edwards Aquifer. Seco Creek and Medina River were selected for focused study because of their importance to recharge of the Edwards Aquifer and their suspected importance as modes of discharge from the Edwards Aquifer. In particular, geophysical imaging of the subsurface of the floodplains of Seco Creek and Medina River was conducted to ascertain evidence of paleo-channel deposits or preferential flow pathways developed in the floodplain sediments.

A series of creeks, including Seco, Parker, Live Oak, Hondo, Verde, Elm, and Quihi, provide surface drainage for the Leona Formation in central Medina County. Based on the results of this investigation, paleo-stream channels in the Seco-Parker Creek floodplain are interpreted to flow south until reaching Highway 90, at which point they flow east eventually coalescing with paleo-stream channels associated with the Live Oak floodplain. This interpretation was based on the detection of a significant paleo-stream channel in the Seco-Parker Creek floodplain to the north, but no paleo-stream channel to the south. Consistent with this conceptualization, paleo-stream channels associated with Hondo, Verde, Elm, and Quihi Creeks were interpreted to flow south and eventually coalesce with the Live Oak paleo-stream channel into a single channel about 8-9 miles south of Hondo. This later interpretation was corroborated with hydrochemical analysis, but not verified or quantified by subsurface geophysical imaging.

Significant paleo-stream channel deposits were detected in the Medina River floodplain. The width of the channel deposits exceeds 1 mile. Local well logs confirm the depth of the channel deposits is uniform at about 7 feet. In the absence of an aquifer test, hydraulic properties for the channel deposits were estimated using documented values for a coarse gravel. Using this information, the capacity for underflow in the Medina River floodplain is estimated at 17,500–175,000 acre-ft/year compared with the average annual surface flow of 146,000 acre-ft/year for the Medina River.

In summary, this investigation determined that there is significant underflow in the Medina River floodplain, negligible underflow in the southern Seco Creek floodplain, and potential underflow in the Live Oak/Hondo Creek floodplain, although the magnitude of this potential remains unquantified at this time.

9. REFERENCES

Barnes, V.E. 1983. Geologic Atlas of Texas: San Antonio Sheet. The University of Texas at Austin, Bureau of Economic Geology.

Bear, J. 1972. Dynamics of Fluids in Porous Media, Dover.

Blome, C.D., J.R. Faith, E.W. Collins, D.E. Pedraza, and K.E. Murray. 2004. Geologic Map Compilation of the Upper Seco Creek area, Medina and Uvalde Counties, South-

Central Texas. U.S. Geological Survey. Open-File Report 2004–1430. Reston, Virginia. 20 pp. + attachments.

Blome, C.D., J.R. Faith, D.E. Pedraza, G.B. Ozuna, J.C. Cole, A.K. Clark, T.A. Small, and R.R. Morris. 2005. Geologic Map of the Edwards Aquifer Recharge Zone, South-Central Texas. U.S. Geological Survey. Scientific Investigations Map 2873. Reston, Virginia.

Blome, C.D., J.R. Faith, and G.B. Ozuna. 2007. Geohydrologic Framework of the Edwards and Trinity Aquifers, South-Central Texas. U.S. Geological Survey. Fact Sheet 2006–3145. Reston, Virginia. 1 pp. + attachments.

Bradley, R.G. 2010. GTA Aquifer Assessment 10-07 MAG: Groundwater Management Area 10 Leona Gravel Aquifer Draft Managed Available Groundwater Estimates. Texas Water Development Board.

Bradley, R.G. 2011. Draft Aquifer Assessment 10-41: Aquifer Assessment for the Leona Gravel Aquifer in Groundwater Management Area 13. Texas Water Development Board.

Buszka, P.M. 1987. Relation of Water Chemistry of the Edwards Aquifer to Hydrogeology and Land Use, San Antonio Region, Texas. U.S. Geological Survey Water-Resources Investigations Report 87–4116. 100 pp.

Clark, A.K. 2003. Geologic Framework and Hydrogeologic Characteristics of the Edwards Aquifer, Uvalde County, Texas. U.S. Geological Survey. Water-Resources Investigations Report 03–4010. Reston, Virginia.

Clark, A.K. and C.A. Journey. 2006. Flow Paths in the Edwards Aquifer, Northern Medina County and Northwestern Uvalde County, Texas, Based on Hydrologic Identification and Geochemical Characterization and Simulation. U.S. Geological Survey Scientific Investigations Report 2006-5200. Reston, Virginia. 48 pp.

Clark, A.K, J.R. Faith, C.D. Blome, and D.E. Pedraza. 2006. Geologic Map of the Edwards Aquifer in Northern Medina and Northeastern Uvalde Counties, South-Central Texas. U.S. Geological Survey Open-File Report 2006-1372. Reston, Virginia. 22 pp. + attachments.

Clark, A.K., C.D. Blome, and J.R. Faith. 2009. Map Showing Geology and Hydrostratigraphy of the Edwards Aquifer Catchment Area, Northern Bexar County, South-Central Texas. U.S. Geological Survey Open-File Report 2009-1008. Reston, Virginia. 24 pp. + attachments.

Collins, E.W. 2000. Geologic Map of the New Braunfels, Texas, 30 × 60 Minute Quadrangle: Geologic Framework of an Urban-Growth Corridor Along the Edwards Aquifer, South-Central Texas. The University of Texas at Austin Bureau of Economic Geology, Miscellaneous Map No. 39.

Collins, E.W. and S.D. Hovorka. 1997. Structure map of the San Antonio Segment of the Edwards Aquifer and Balcones Fault Zone, South-Central Texas: Structural Framework of a Major Limestone Aquifer: Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties. The University of Texas at Austin, Bureau of Economic Geology. Miscellaneous Map No. 38. Scale 1:250,000. 2 sheets.

Doyle, F.L. 2003. Ancestral Medina River and alluvial surfaces adjacent to the Balcones Escarpment: Bexar and Medina Counties, Texas. South Texas Geological Society Bulletin. 63(7). pp. 25-32.

Falhlquist, L. and A.F. Ardis., 2004. Quality of Water in the Trinity and Edwards Aquifers, South-Central Texas, 1996-1998. U.S. Geological Survey Scientific Investigations Report 2004-5201. Reston, Virginia. 25 pp.

Ferrill, D.A., A.P. Morris, J.A. Stamatakos, and D.W. Sims. 2000. Crossing Conjugate Normal Faults. Bulletin of the American Association of Petroleum Geologists. V. 84. pp. 1543–1559.

Ferrill, D.A., D.W. Sims, D.J. Waiting, A.P. Morris, N. Franklin, and A. Schultz.2004. Structural Framework of the Edwards Aquifer Recharge Zone, South-Central Texas. Geological Society of America Bulletin. V. 116. pp. 407-418.

Ferrill, D.A., D.W. Sims, N. Franklin, A.P. Morris, and D.J. Waiting. 2005. Structural Controls on the Edward Aquifer/Trinity Aquifer Interface in the Helotes Quadrangle, Texas. Final report prepared for the Edwards Aquifer Authority and the U.S. Army Corps of Engineers.

Foley, L.L. 1926. Mechanics of the Balcones and Mexia Faulting. Bulletin of the American Association of Petroleum Geologists. V. 10. No. 12. pp. 1261–1269.

Freeze, R.A. and J.A. Cherry. 1979. *Groundwater*. Englewood Cliffs, New Jersey: Prentice Hall.

George, P. 2010. GTA Aquifer Assessment 09-01: Texas Water Development Board, GTA Aquifer Assessment Report 09-01 Report, 14 pp.

Green, R.T., F.P. Bertetti, N.M. Franklin, A.P. Morris, D.A. Ferrill, and R.V. Klar. 2006. Evaluation of the Edwards Aquifer in Kinney and Uvalde Counties, Texas. Final contract report prepared for the Edwards Aquifer Authority by Southwest Research Institute. San Antonio, Texas.

Green, R.T., F.P. Bertetti, B.P. Wilcox, and R.N. McGinnis. 2008a. Investigation of the Groundwater Systems in the Wintergarden Groundwater Conservation District—Phase II. Southwest Research Institute. Conducted for the Wintergarden Groundwater Conservation District.

Green, R.T., J.R. Winterle, and J.D. Prikryl. 2008b. Discharge from the Edwards Aquifer through the Leona River Floodplain, Uvalde, Texas. Journal of American Water Resources Association. Vol. 44. No. 4. pp. 887-901. DOI: 10.1111/j.1752-1688.2008.00187.x.

Green, R.T., F.P. Bertetti, and R.N. McGinnis. 2009a. Investigation of the Secondary Aquifers in Uvalde County. Southwest Research Institute. Contract project conducted for the Uvalde County Underground Water Conservation District. 74 pp.

Green, R.T., F.P. Bertetti, and R.N. McGinnis. 2009b. Measuring Floodplain Hydraulics of the Frio River Where it Overlies the Edwards Aquifer. Contract project conducted for the Edwards Aquifer Authority. 40 pp.

Groschen, G.E. 1996. Hydrogeologic Factors that Affect the Flowpath of Water in Selected Zones of the Edwards Aquifer in the San Antonio Region, Texas. U.S. Geological Survey Water-Resources Investigations Report 96—4046. 73 pp.

Hamilton, J.M., R. Esquilin, and G.M. Schindel. 2006. Edwards Aquifer Authority Synoptic Water Level Program 1999—2004 Report. Report No. 06-02. Edwards Aquifer Authority. San Antonio. Texas.

Hamilton, J.M., S. Johnson, J. Mireles, R. Esquilin, C. Burgoon, G. Luevan, D. Gregory, R. Gloyd, J. Sterzenback, and R. Mendoza. 2008. Edwards Aquifer Authority Hydrologic Data Report for 2007. Report No. Report 09-02. Edwards Aquifer Authority. San Antonio, Texas.

Holt, C.L.R. 1956. Geology and Water-Resources of Medina County, Texas. Texas Board of Water Engineers Bulletin 5601. 97 pp.

Holt, C.L.R., Jr. 1959. Geology and Ground-Water resources of Medina County, Texas. U.S. Geological Survey Water-Supply Paper 1422. Reston, Virginia. 213 pp.

Johnson, J., G. Schindel, and G. Veni. 2010. Tracing Groundwater Flowpaths in the Edwards Aquifer Recharge Zone, Panther Springs Creek Basin, Northern Bexar County, Texas. Edwards Aquifer Authority. Report 10-01. 122 pp.

Lambert, R.B., K.C. Grimm, and R.W. Lee. 2000. Hydrogeology, Hydrologic Budget, and Water Chemistry of the Medina Lake Area, Texas. U.S. Geological Survey Water-Resources Investigations Report 00-4148. Reston, Virginia. 54 pp. + attachments.

LBG-Guyton Associates and Aqua Terra Consultants. 2005. HSPF Recharge Models for the San Antonio Segment of the Balcones Fault Zone Edwards Aquifer. Prepared for the Edwards Aquifer Authority.

Loke, M.H. 2004.. Lecture Notes on 2D and 3D Electrical Imaging Surveys. (Revision date: 22nd July 2004). http://www.geoelectrical.com/download.html.

Lowry, M.V. and B.E. Couch . 2002. Phase I Leona Gravel Aquifer Study: Prepared for the Medina County Groundwater Conservation District by Turner Collie & Braden Inc. 51 pp.

Maclay, R.W. 1995. Geology and Hydrogeology of the Edwards Aquifer in the San Antonio Area, Texas. U.S. Geological Survey Water-Resources Investigations Report 95-4186. Reston, Virginia. 64 pp. + attachments.

Maclay, R.W., T.A. Small, and P.L. Rettman. 1981. Location and Analysis of Borehole Data for the Edwards Aquifer in the San Antonio Area, Texas. Texas Department of Water Resources. LP-139. 88 pp.

Maclay, R.W. and T.A. Small. 1983. Hydrostratigraphic Subdivisions and Fault Barriers of the Edwards Aquifer, South-Central Texas. U.S.A. Journal of Hydrology. V. 61. pp. 127–146.

Maclay, R.W. and T.A. Small. 1984. Carbonate Geology and Hydrology of the Edwards Aquifer in the San Antonio Area, Texas: U.S. Geological Survey Open-File Report OFR 83-537. Reston, Virginia. 72 pp. 14 sheets.

Maclay, R.W. and L.F. Land. 1988. Simulation of Flow in the Edwards Aquifer, San Antonio Region, Texas, and Refinement of Storage Flow Concepts. U.S. Geological Survey Water-Supply Paper 2336. Reston, Virginia. 48 pp.

Murray, G.E. 1961. Geology of the Atlantic and Gulf Coastal Province of North America. New York. Harper and Brothers. 692 pp.

Oetting, G.C., J.L. Banner, and J.M. Sharp, Jr. 1996. Regional Controls on the Geochemical Evolution of Saline Groundwaters in the Edwards Aquifer, Central Texas. Journal of Hydrology. Vol. 181. pp. 251–283.

Ockerman, D.J. 2005. Simulation of Streamflow and Estimation of Recharge to the Edwards Aquifer in the Hondo Creek, Verde Creek, and San Geronimo Creek Watersheds, South-Central Texas. U.S. Geological Survey Scientific Investigations Report 2005-5252. Reston, Virginia. 37 pp.

Pantea, M.P., J.C. Cole, B.D. Smith, J.R. Faith, C.D. Blome, and D.V. Smith. 2008. Three-Dimensional Geologic Model in the Upper Seco Creek Area, Medina and Uvalde Counties, South-Central Texas. U.S. Geological Survey Scientific Investigations Report 2008-5153. Reston, Virginia. 9 pp. + attachments.

Parkhurst, D.L. and C.A.J. Appelo. 1999. User's Guide to PHREEQC (Version2)—A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and

Inverse Geochemical Calculations. U.S. Geological Survey Water-Resources Investigations Report 99–4259. 310 pp.

Pearson, F.J. and P.L. Rettman. 1976. Geochemical and Isotopic Analyses of Waters Associated with the Edwards Limestone Aquifer, Central Texas. Edwards Underground Water District Report. U.S. Geological Survey. Reston, Virginia. 35 pp.

Pedraza, D.E. and D.J. Ockerman. 2012. Watershed Modeling Applications in South Texas. U.S. Geological Survey Fact Sheet 2012-3005. Reston, Virginia.

Piper, A.M. 1944. A Graphic Procedure in the Geochemical Interpretation of Water Analyses. Transactions of the American Geophysical Union. Vol. 25. pp. 914–923.

Rives, J.S. 1967. Structural and Stratigraphic Traps Related to Extrusive Rocks in South-Central Texas: AAPG Bulletin. Volume 51. DOI: 10.1306/5D25C241-16C1-11D7-8645000102C1865D.

Sharp, J.M., Jr., and J.L. Banner. 1997. The Edwards Aquifer: A Resource in Conflict. GSA Today. Vol. 7. pp. 1–9

Slattery, R.N. and L.D. Miller. 2004. A Water-Budget Analysis of Medina and Diversion Lakes and the Medina/Diversion Lake System, with Estimated Recharge to the Edwards Aquifer, San Antonio Area, Texas. U.S. Geological Survey Scientific Investigations Report 2004–5209. U.S. Geological Survey. Reston, Virginia. 41 pp.

Small, T.A. and A.K. Clark. 2000. Geologic Framework and Hydrogeologic Characteristics of the Edwards Aquifer Outcrop, Medina County, Texas. U.S. Geological Survey Water-Resources Investigation 00–4195. U.S. Geological Survey. Reston, Virginia. 10 pp. + attachments.

Smith, D.V., B.D. Smith, , and P.L. Hill. 2002. Aeromagnetic Survey of Medina and Uvalde Counties, Texas. U.S. Geological Survey Open-File-Report 02-0049. Reston, Virginia.

Smith, D.V., R.R. McDougal, , B.D. Smith, , and C.D. Blome. 2008. Distribution of Igneous Rocks in Medina and Uvalde Counties, Texas, as Inferred from Aeromagnetic Data. U.S. Geological Survey Scientific Investigations Report 2007–5191. U.S. Geological Survey. Reston, Virginia.

Stein, W.G. and G.B. Ozuna. 1996. Geological Framework and Hydrogeologic Characteristics of the Edwards Aquifer Recharge Zone, Bexar County, Texas. U.S. Geological Survey Water-Resources Investigations Report 95-4030. 1:75,000 scale. Reston, Virginia. 8 pp. 1 plate.

Texas Water Development Board. 2011. Groundwater Database Download. http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.asp. February 3, 2011.

Weeks, A.W. 1945. Balcones, Luling, and Mexica Fault Zones in Texas: Bulletin of the American Association of Petroleum Geologists. Vol. 29. pp. 1733–1737.

Young, K. 1972. Mesozoic History, Llano Region, *in* V.E., Barnes, W.C. Bell, S.E. Clabaugh, P.E. Cloud, Jr., R.V. McGehee, P.U. Rodda, and K. Young, eds. Geology of the Llano Region and Austin Area, Field Excursion: The University of Texas at Austin Bureau of Economic Geology Guidebook 13. 154 pp.

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Calculations, data reduction and analysis, and/or numerical analyses reported here were performed consistent with generally accepted engineering and scientific practices. Procedures were used and results were documented in accordance with the Geosciences and Engineering Division Quality Assurance Manual. The graphics generated and presented here, along with any conclusions, opinions, and recommendations reported, are based on the scope of work and other requirements established in the contract, data developed by the contractor and obtained from other sources, and calculations and analyses performed as described in the foregoing paragraphs. These conclusions, opinions, and recommendations apply to the conditions prevailing at the time the services were performed and, therefore, apply only to the purposes, locations, time frames, and other conditions stated in the report. The contractor makes no warranty, expressed or implied, with respect to use of this report or the results contained herein for other purposes, locations, time frames, or conditions.

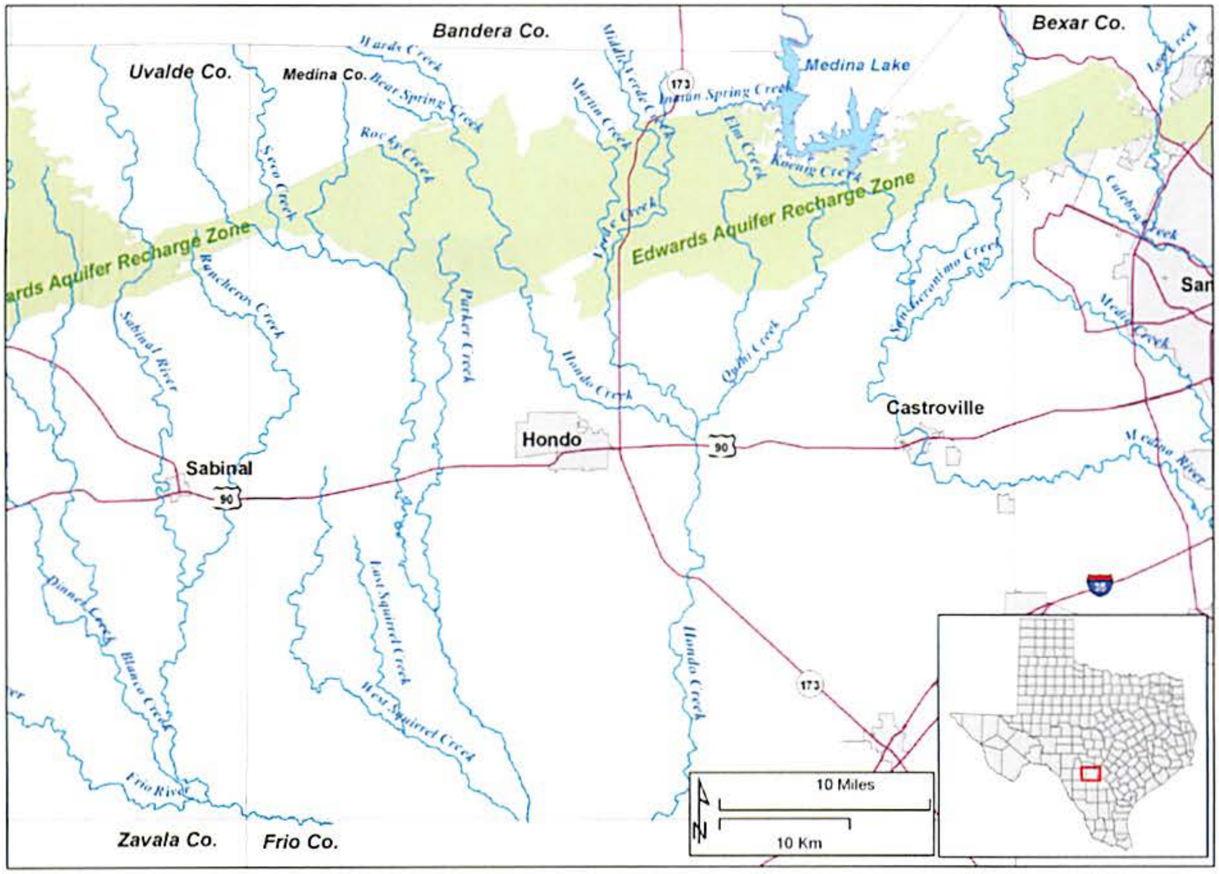

Figure 1: Map of Medina County.

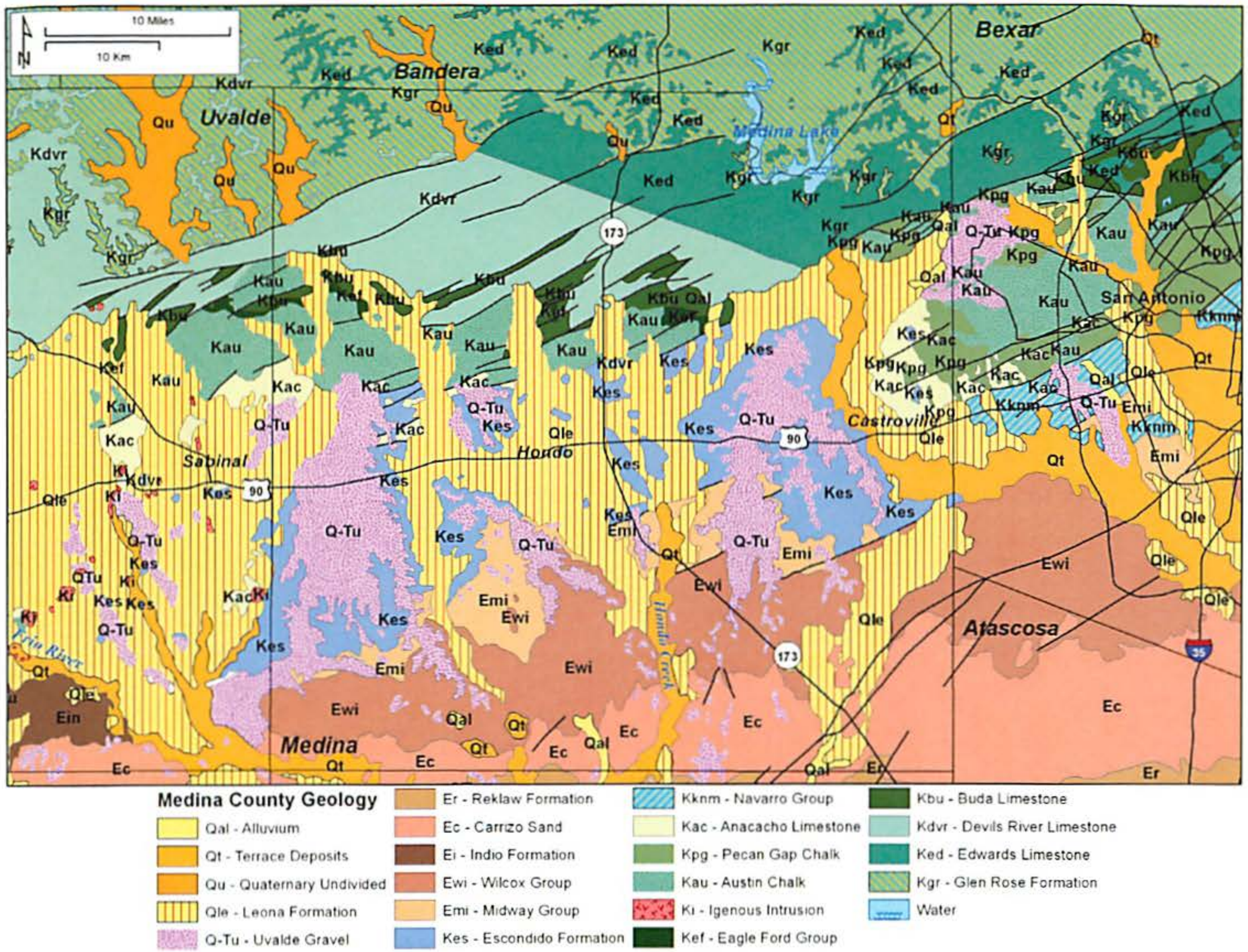

Figure 2: Geological map of Medina County (map data adapted from Blome et al., 2004).

<table>
<tr><th>Geo-
Chronology</th><th colspan="2">STUDY AREA
Devils River Trend West   San Marcos Platform East</th><th>Aquifer</th></tr>
<tr><td rowspan="2">Quaternary</td><td colspan="2">Alluvium</td><td rowspan="9"></td></tr>
<tr><td colspan="2">Leona Formation</td></tr>
<tr><td>Tertiary</td><td colspan="2">Uvalde Gravel</td></tr>
<tr><td rowspan="6">Late Cretaceous</td><td colspan="2">Escondido Formation</td></tr>
<tr><td colspan="2">Anacacho Limestone</td></tr>
<tr><td colspan="2">Austin Chalk</td></tr>
<tr><td colspan="2">Eagle Ford Shale</td></tr>
<tr><td colspan="2">Buda Limestone</td></tr>
<tr><td colspan="2">Del Rio Clay</td></tr>
<tr><td rowspan="4">Early Cretaceous</td><td colspan="2">Georgetown Fm.</td><td rowspan="3">Edwards Aquifer</td></tr>
<tr><td rowspan="2">Devils River Fm.</td><td>Person Fm.</td></tr>
<tr><td>Kainer Fm.</td></tr>
<tr><td colspan="2">Glen Rose Limestone</td><td>Trinity Aquifer</td></tr>
</table>

Figure 3: Stratigraphic column for Medina County.

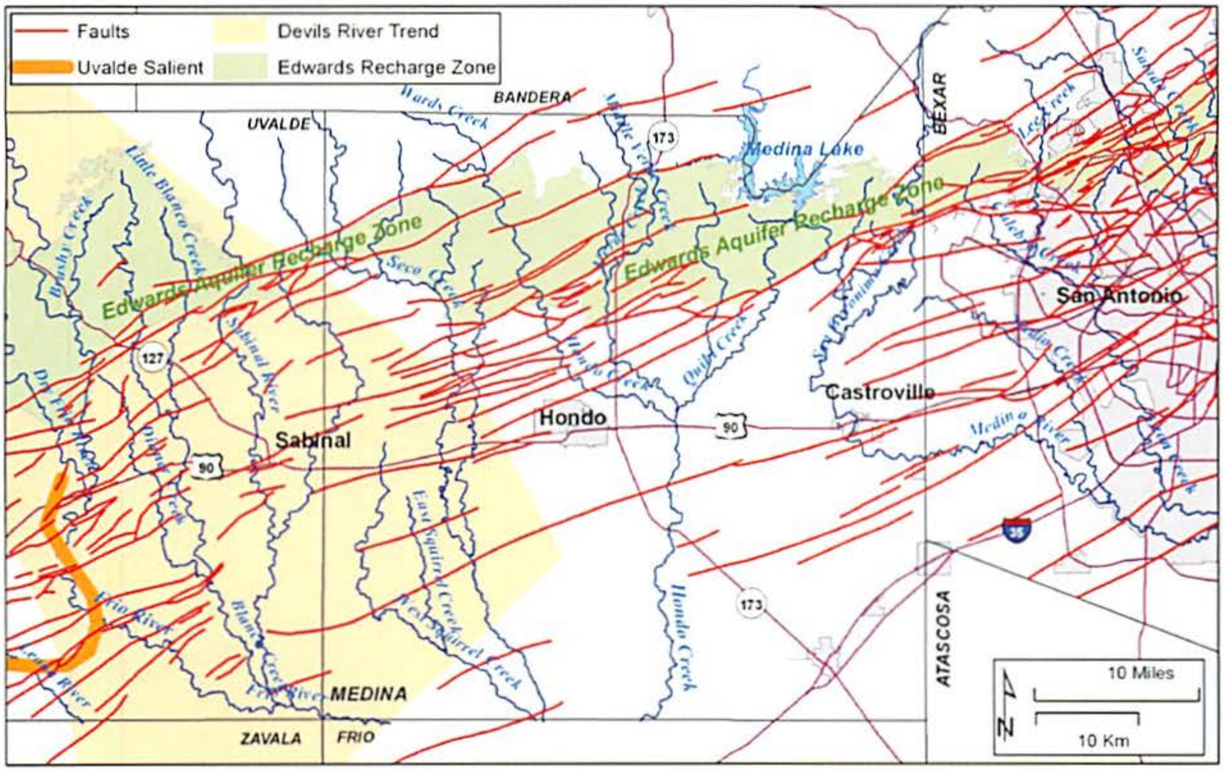

Figure 4: Geological structure map of Medina County illustrating Balcones fault system.

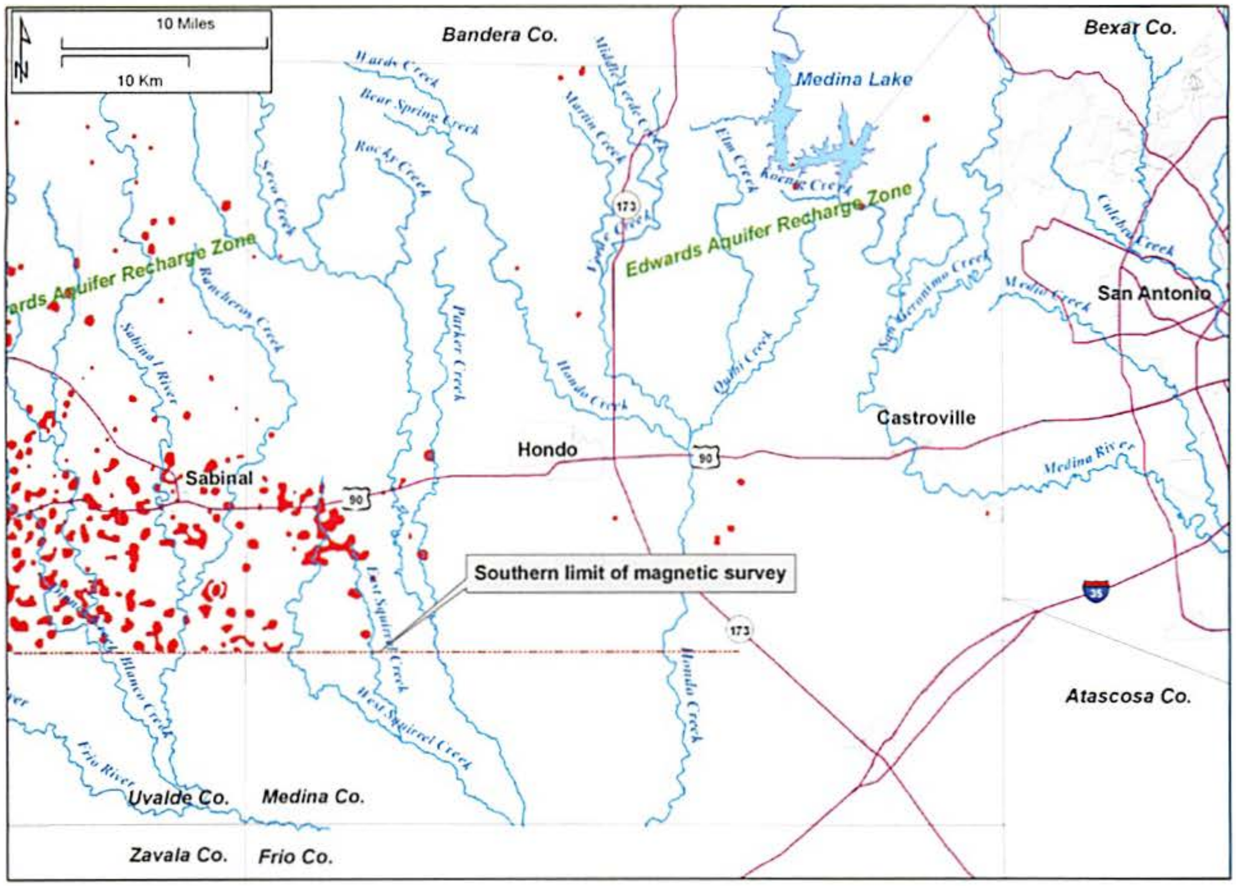

Figure 5: Igneous intrusion locations (red) inferred using results from an aeromagnetic survey (Smith et al., 2008).

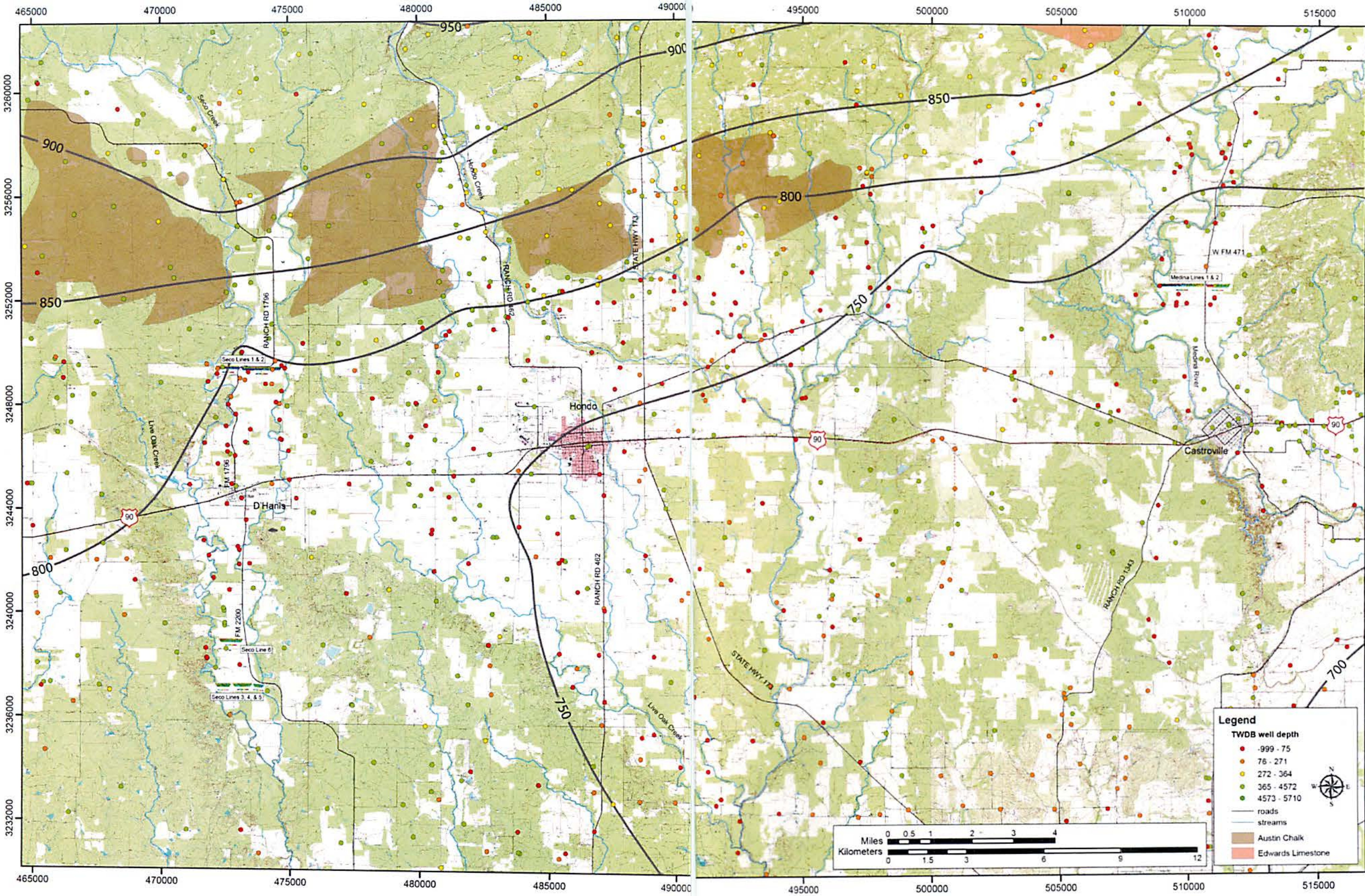

Figure 6: Potentiometric surface of the Edwards Aquifer in Medina County, Texas.

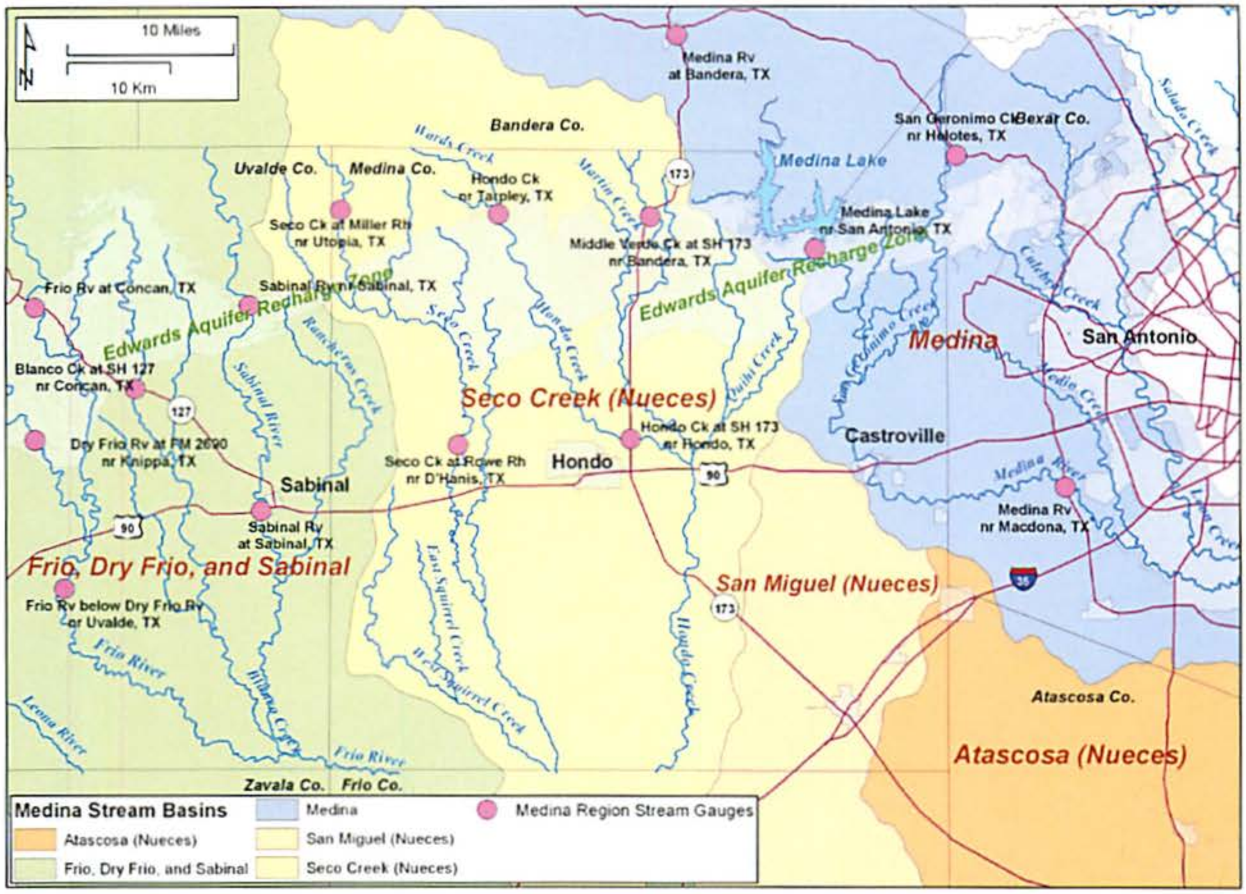

Figure 7: River watershed basins and surface water gauging stations operated by the U.S. Geological Survey in Medina County, Texas.

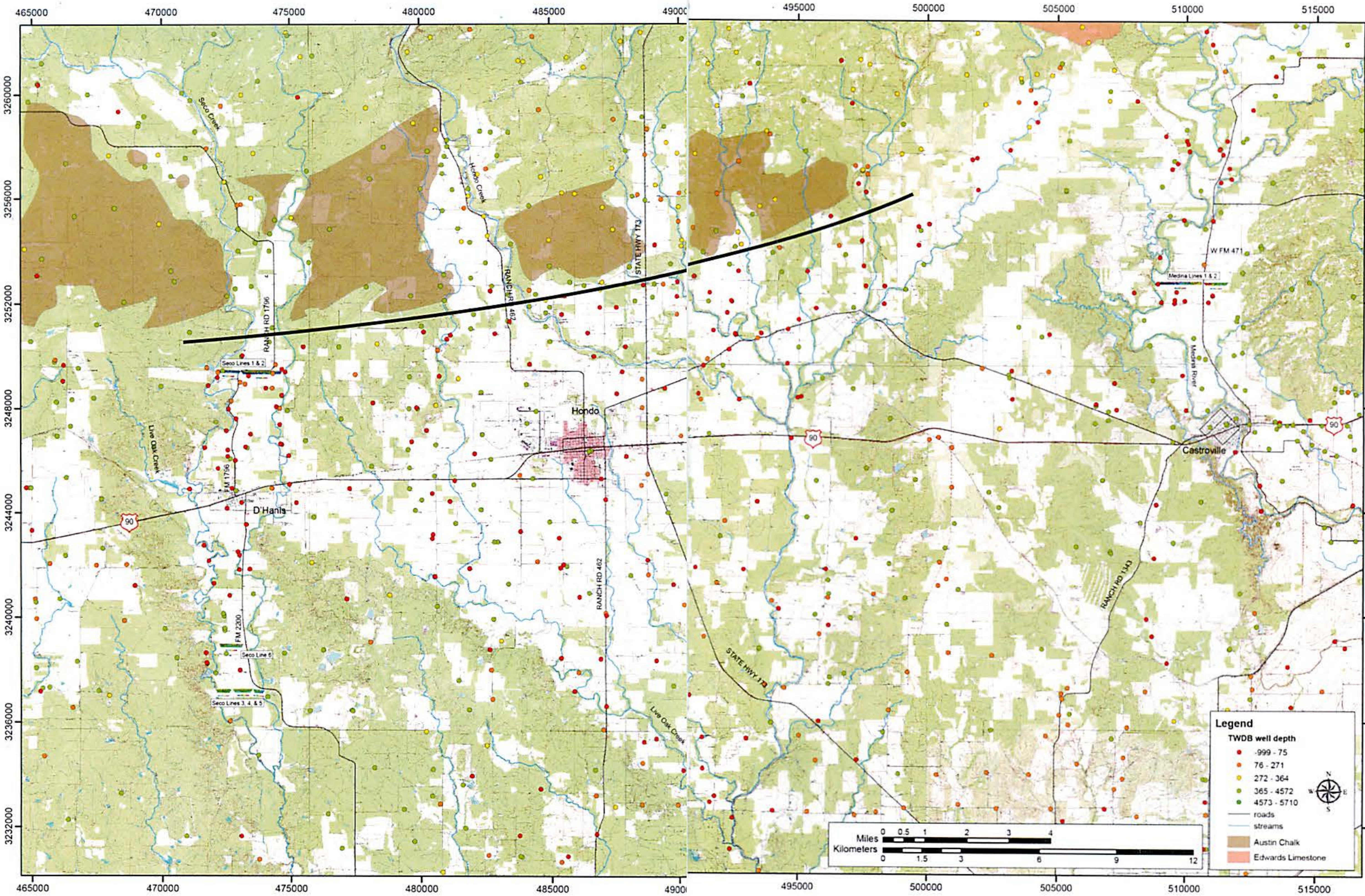

Figure 8. Topographic map of Medina County illustrating wells categorized by depth. Locations of eletrical resistivity transects are indicated in the Seco and Parker Creek floodplain and the Medina River floodplain. A black line denotes the downdip boundary of the Austin Chalk recharge zone and the upstream extent of the paleo-stream channels.

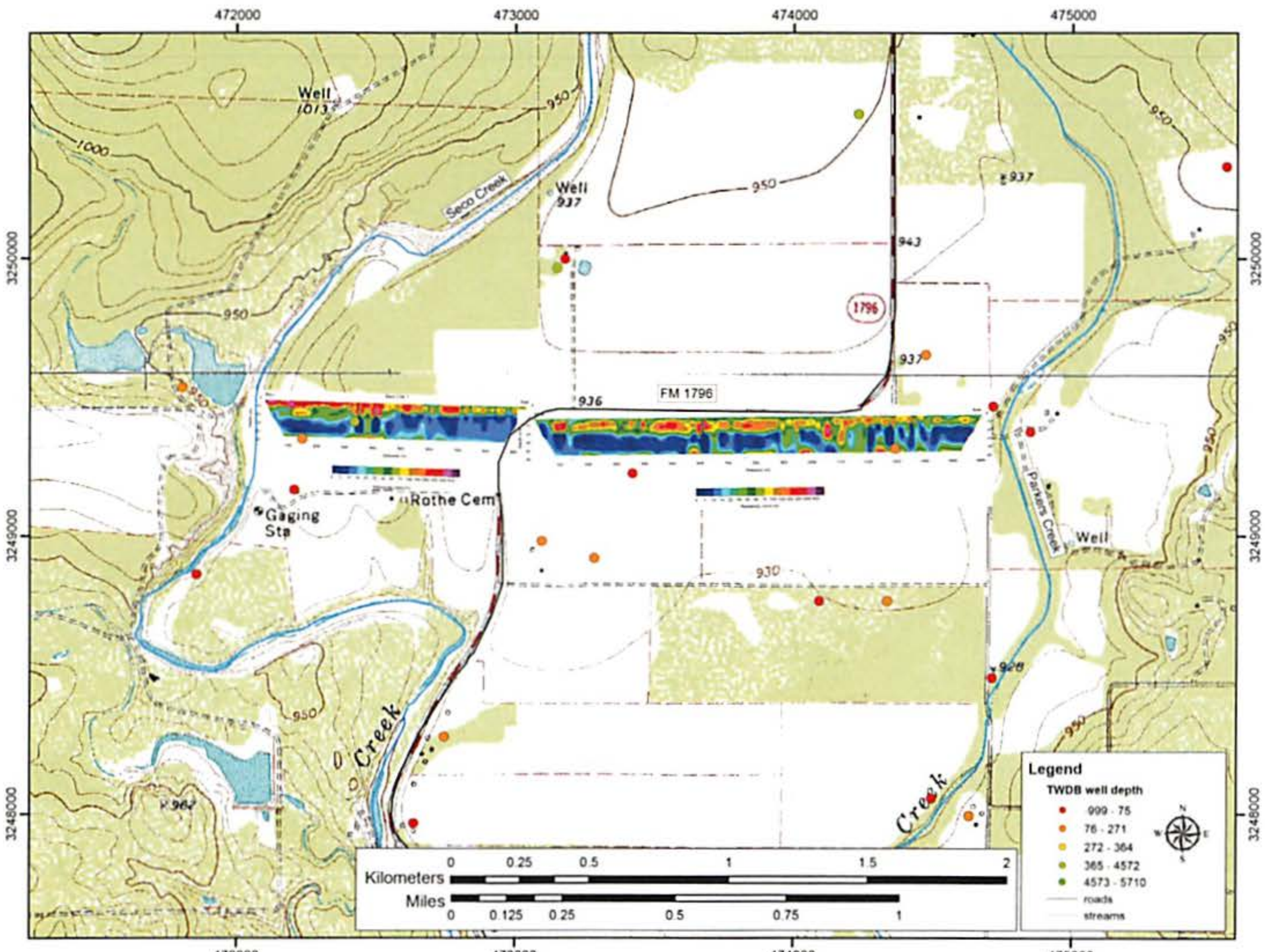

Figure 9. Topgraphic map of northern floodplain of Seco and Parker creeks illustrating locations of electrical resistivity transects Seco 1 (left) and Seco 2 (right). Included are wells from the Texas Water Development Board (2011) database.

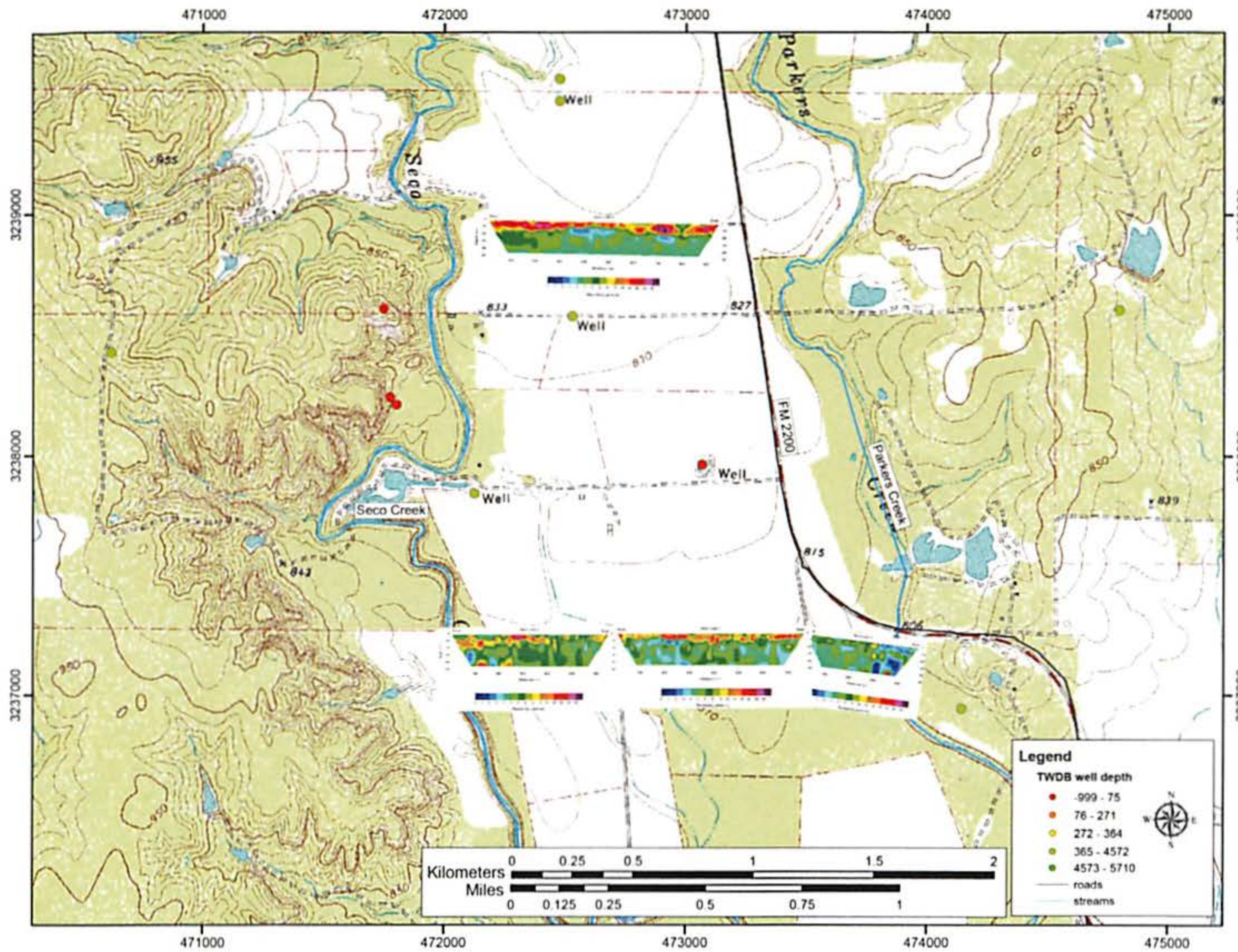

Figure 10. Topgraphic map of southern floodplain of Seco and Parker creeks illustrating locations of electrical resistivity transects Seco 3 (north), Seco 4 (lower left), Seco 5 (lower center), and Seco 6 (lower right). Included are wells from the Texas Water Development Board (2011) database.

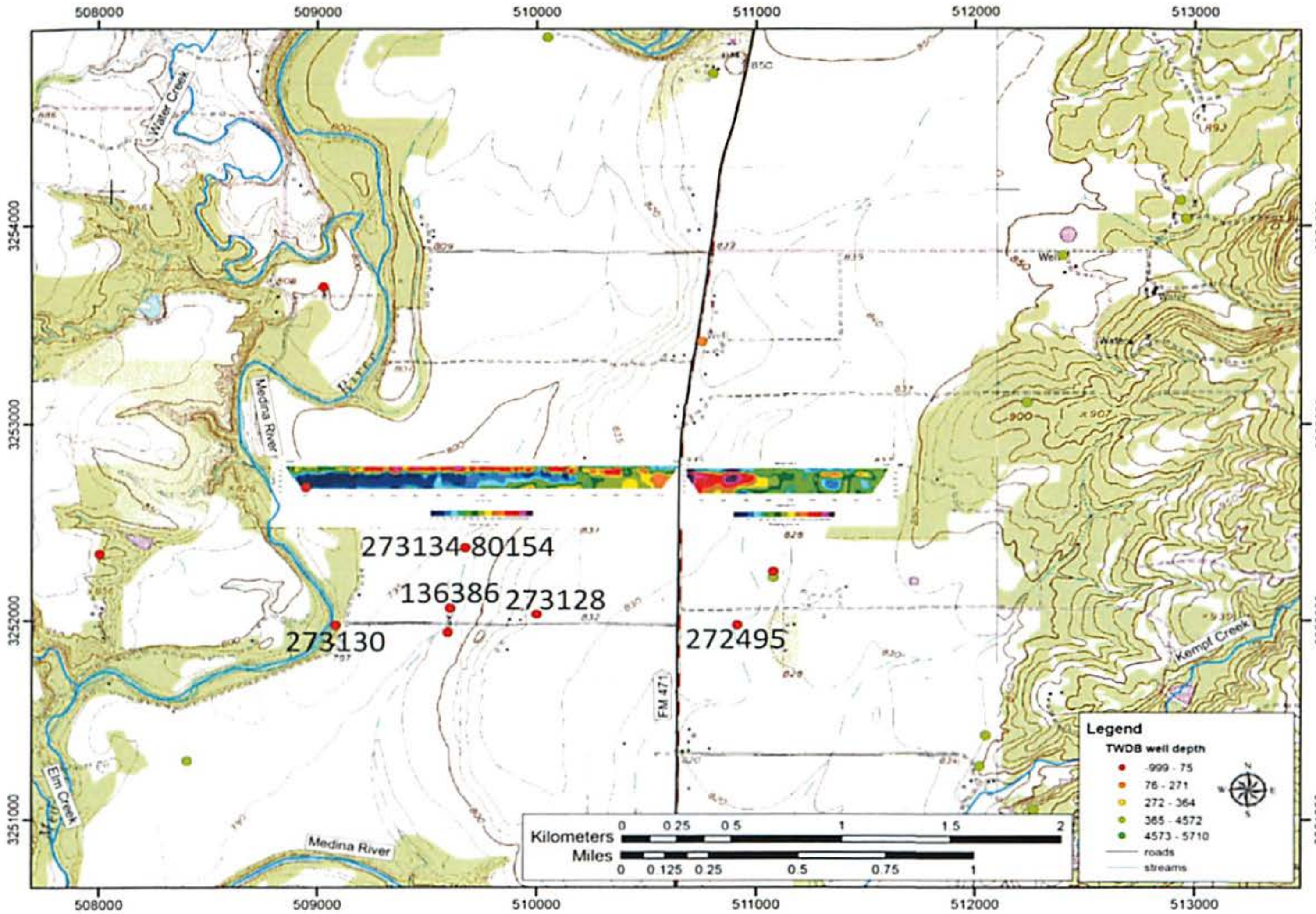

Figure 11. Topgraphic map of Medina River floodplain illustrating locations of electrical resistivity transects Medina 1 (left) and Medina 2 (right). Included are wells from the Texas Water Development Board (2011) database.

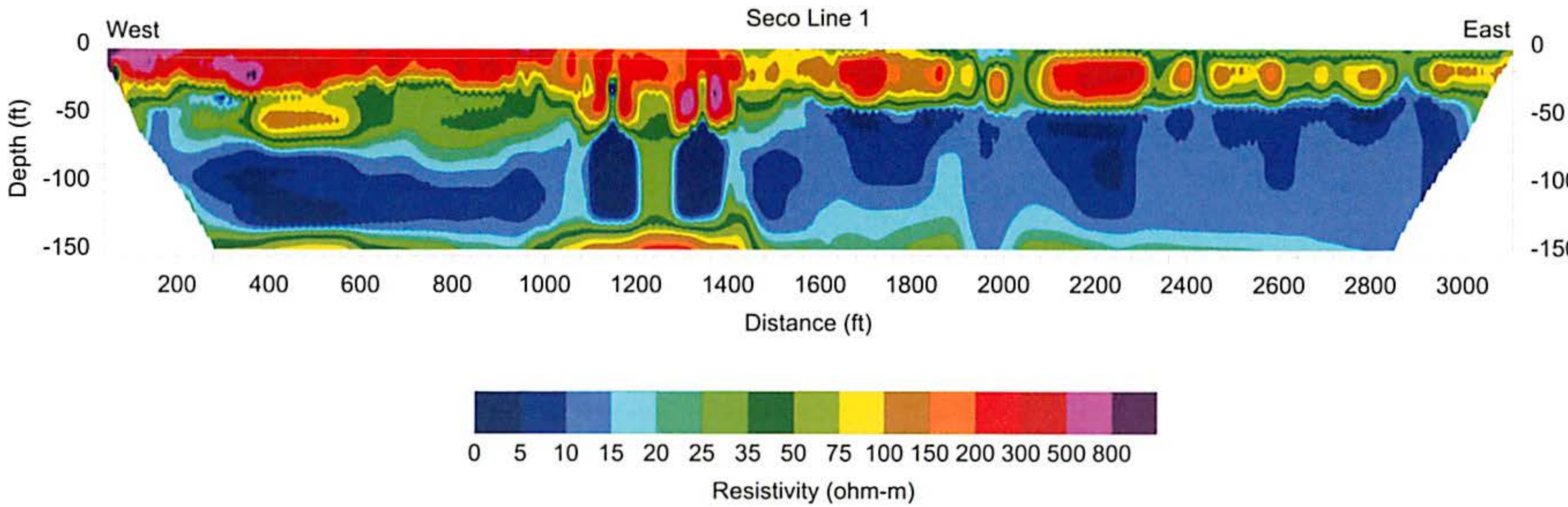

Figure 12. Vertical profile of electrical resistivity values calculated for the Seco Line 1 located at the northern Seco and Parker Creek floodplain transect. Leona Formation is interpreted as zones with resistivity above 200 ohm-m. 3:1 vertical exageration.

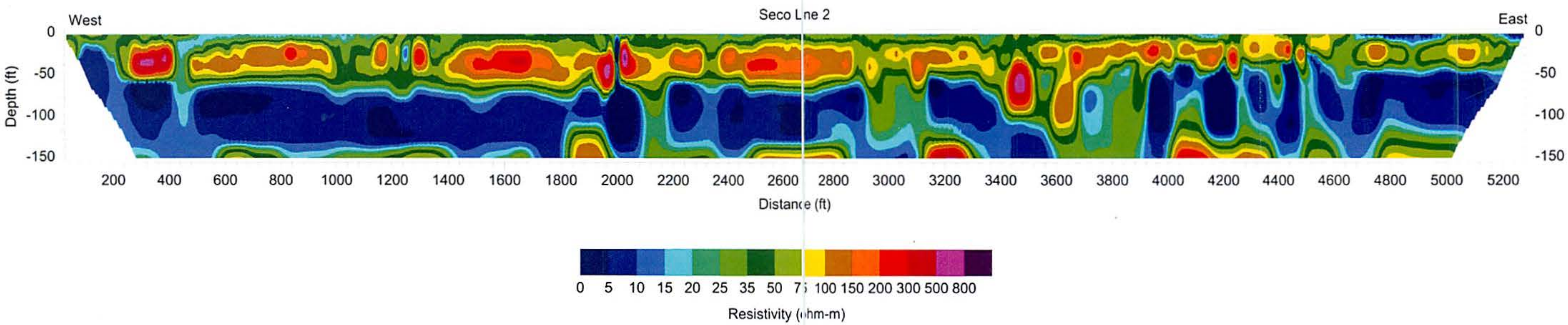

Figure 13. Vertical profile of electrical resistivity values calculated for the Seco Line 2 located at the northern Seco and Parker Creek floodplain transect. Leona Formation is interpreted as zones with resistivity above 200 ohm-m. 3:1 vertical exageration.

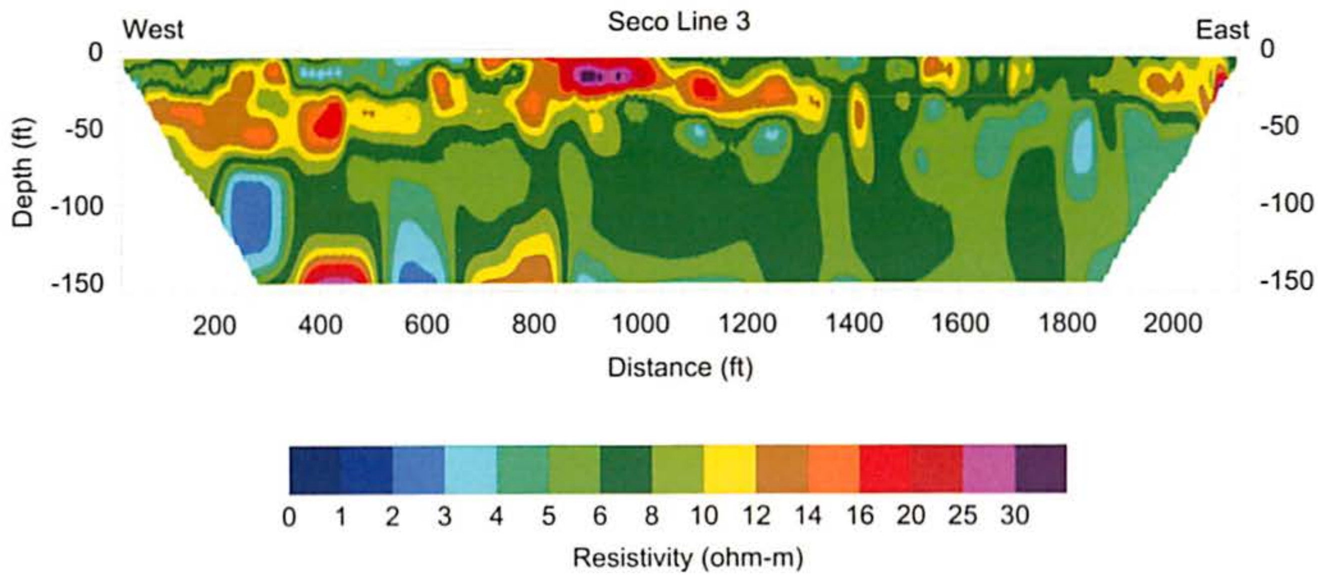

Figure 14. Vertical profile of electrical resistivity values calculated for the Seco Line 3 located at the southern Seco and Parker Creek floodplain transect. 3:1 vertical exageration.

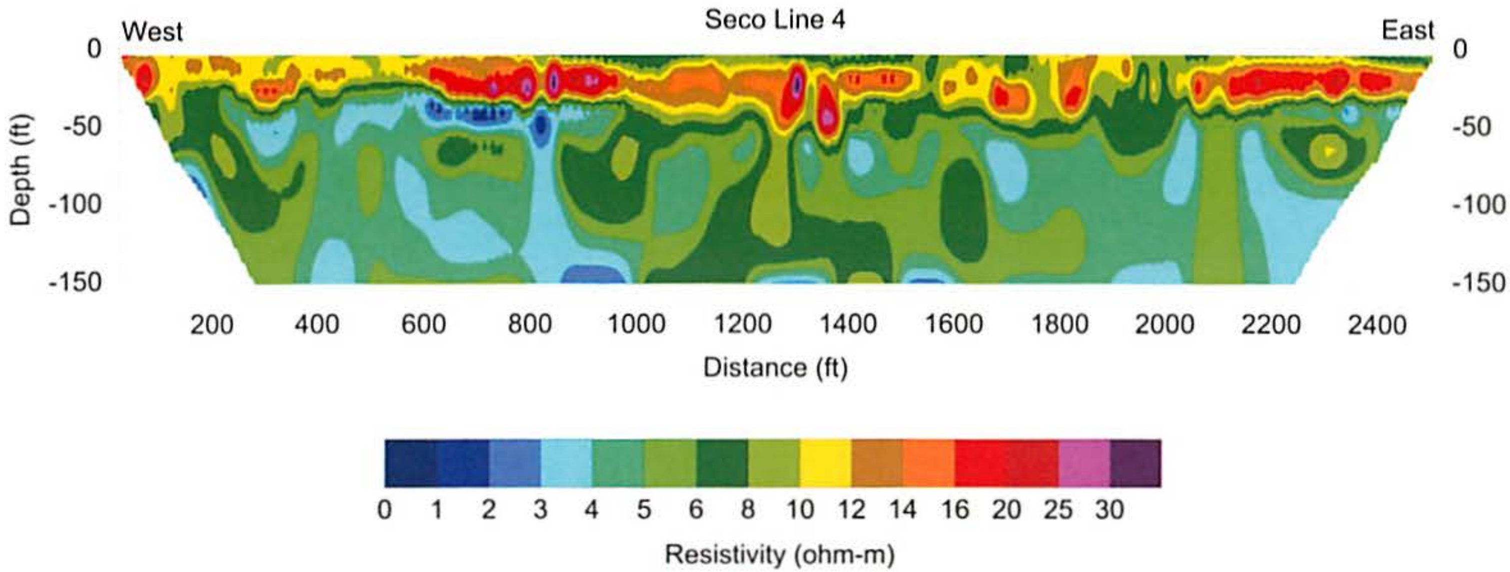

Figure 15. Vertical profile of electrical resistivity values calculated for the Seco Line 4 located at the southern Seco and Parker Creek floodplain transect. 3:1 vertical exageration.

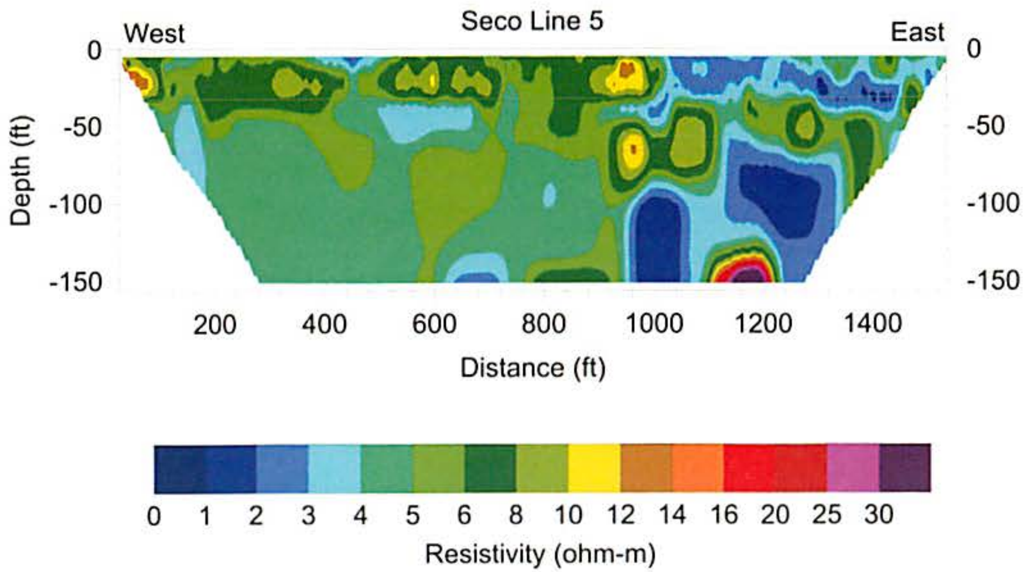

Figure 16. Vertical profile of electrical resistivity values calculated for the Seco Line 5 located at the southern Seco and Parker Creek floodplain transect. 3:1 vertical exageration.

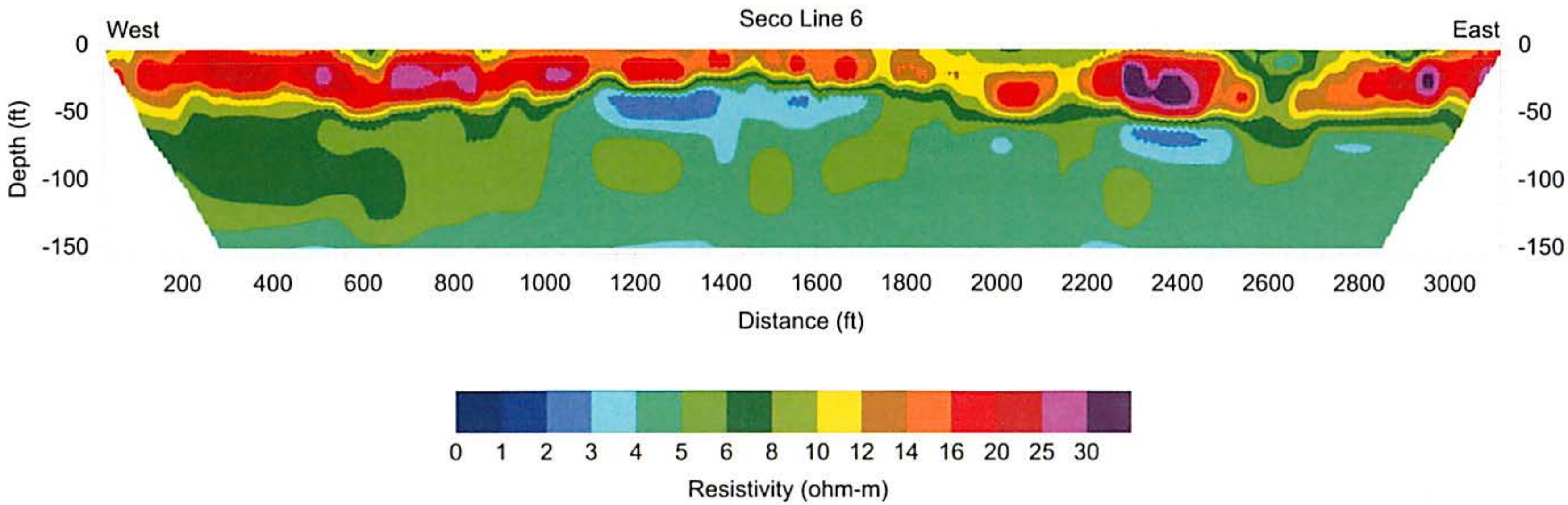

Figure 17. Vertical profile of electrical resistivity values calculated for the Seco Line 6 located at the southern Seco and Parker Creek floodplain transect. 3:1 vertical exageration.

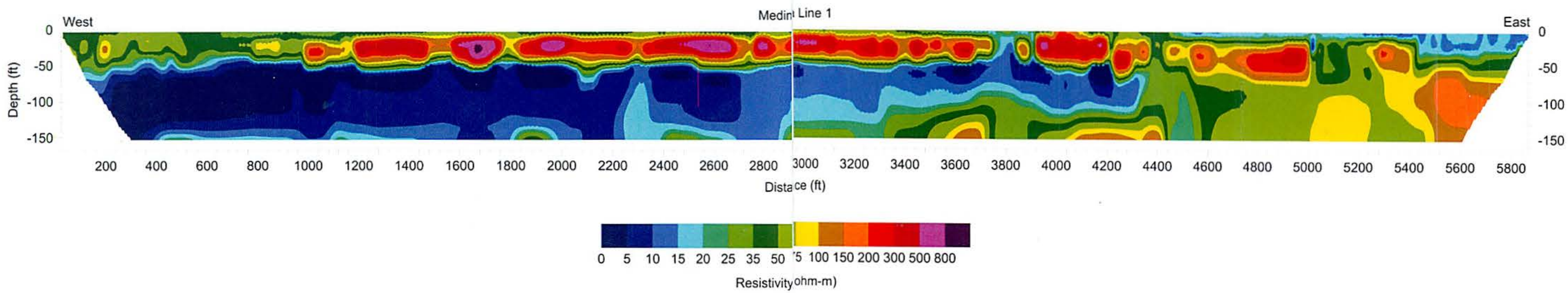

Figure 18. Vertical profile of eletrical resistivity values calculated for the Medin Line 1 located at the Medina River floodplain transect.

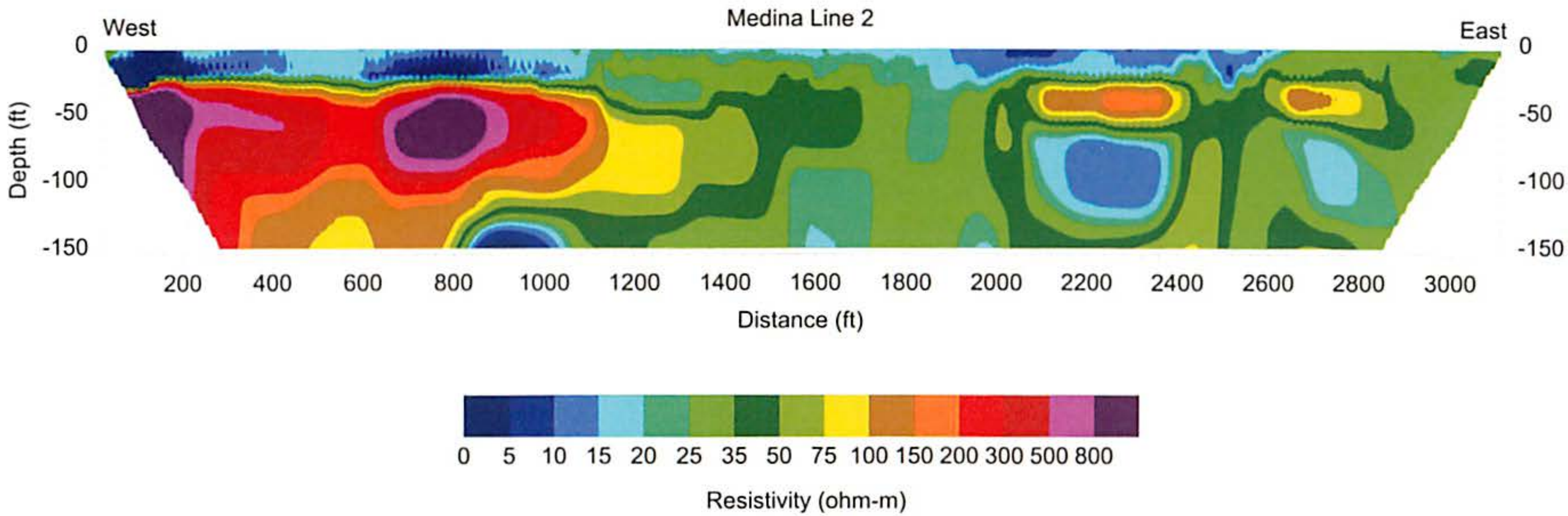

Figure 19. Vertical profile of electrical resistivity values calculated for the Medina Line 2 located at the Medina River floodplain transect. Leona Formation is interpreted as zones with resistivity above 200 ohm-m. 3:1 vertical exageration.

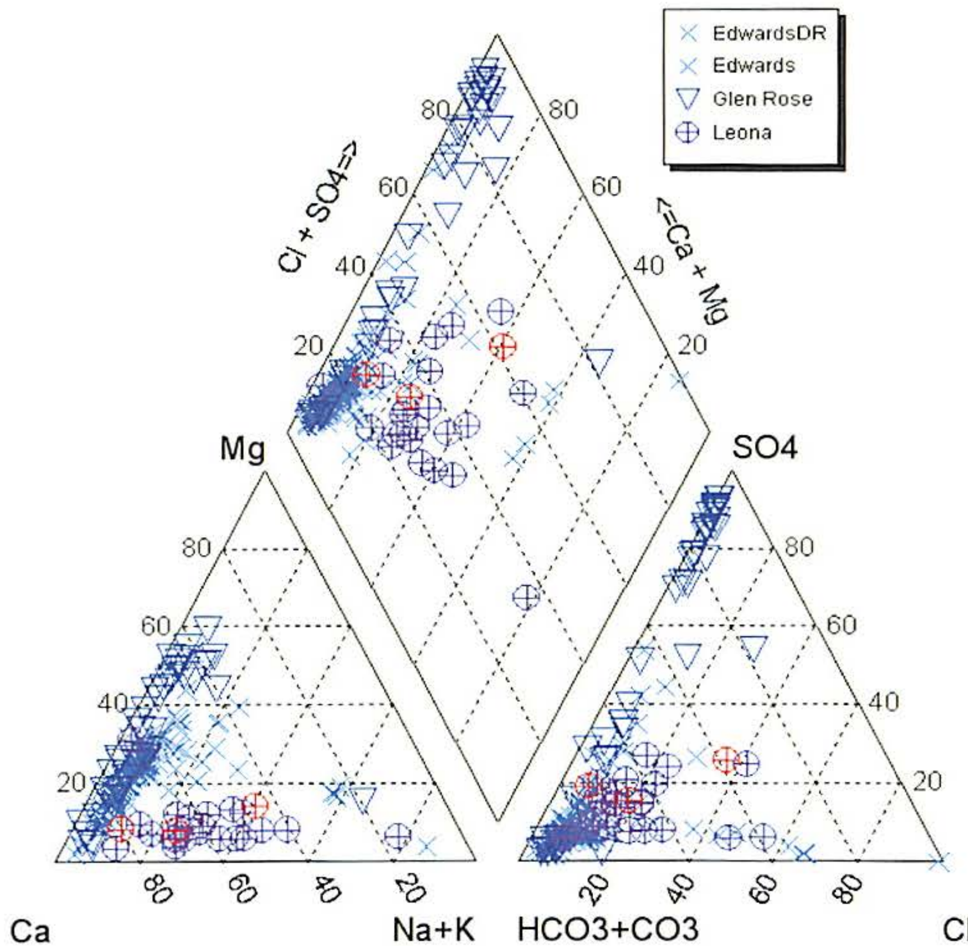

Figure 20: Trilinear plot of water chemistry from Edwards, Trinity, and Leona Formation wells. Data for Edwards and Edwards - Devils River trend wells are not separated in the plot. Two saline water trends in the plot include a transition from dilute to Ca-SO_4 type waters and a transition from dilute to Na-Cl type waters

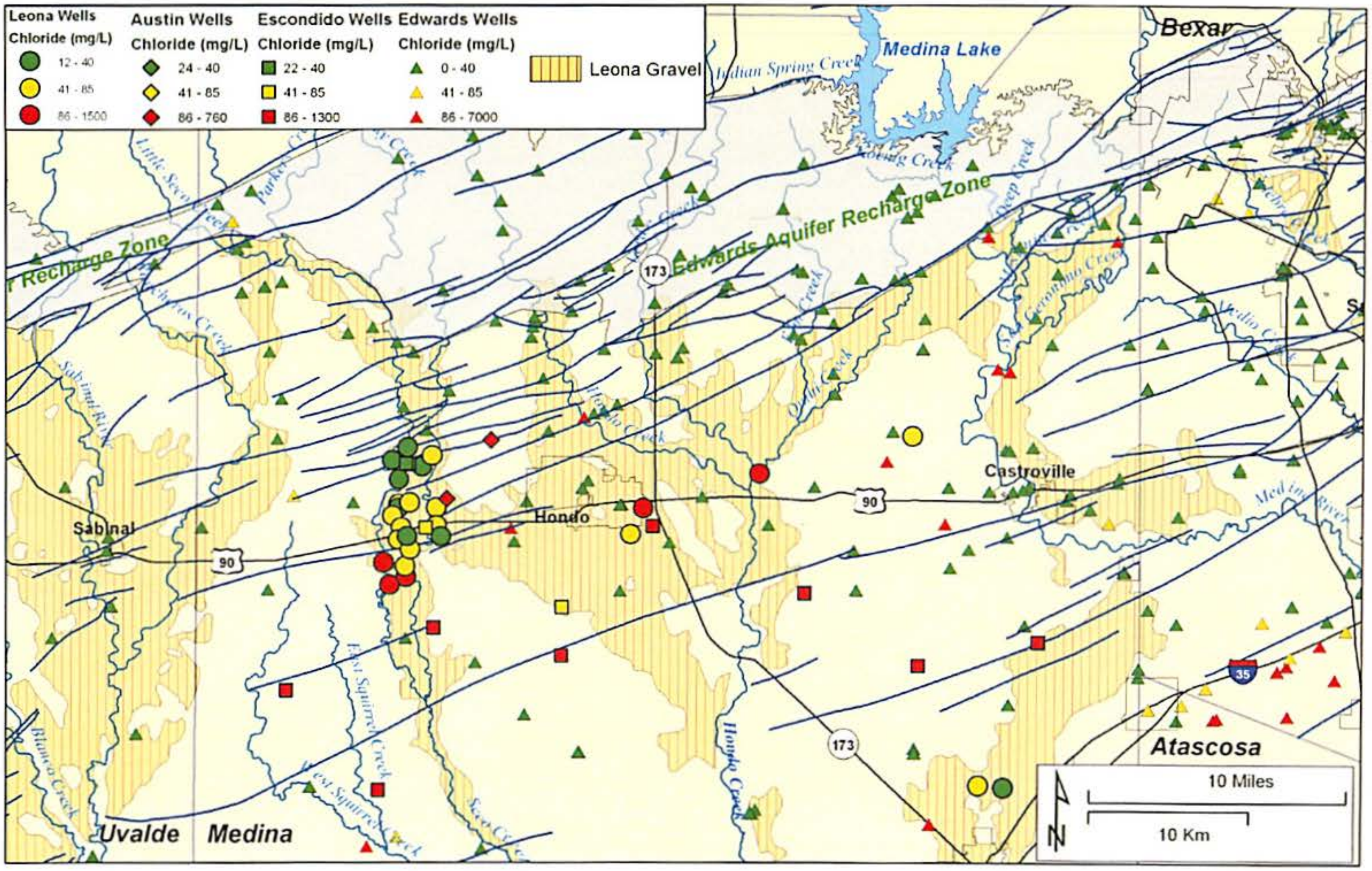

Figure 21: Map of Leona Formation, Austin Chalk, Escondido Formation, and Edwards Aquifer wells with available water chemistry. Chloride concentration values for water samples from the wells are shown. Major faults are denoted by blue lines.

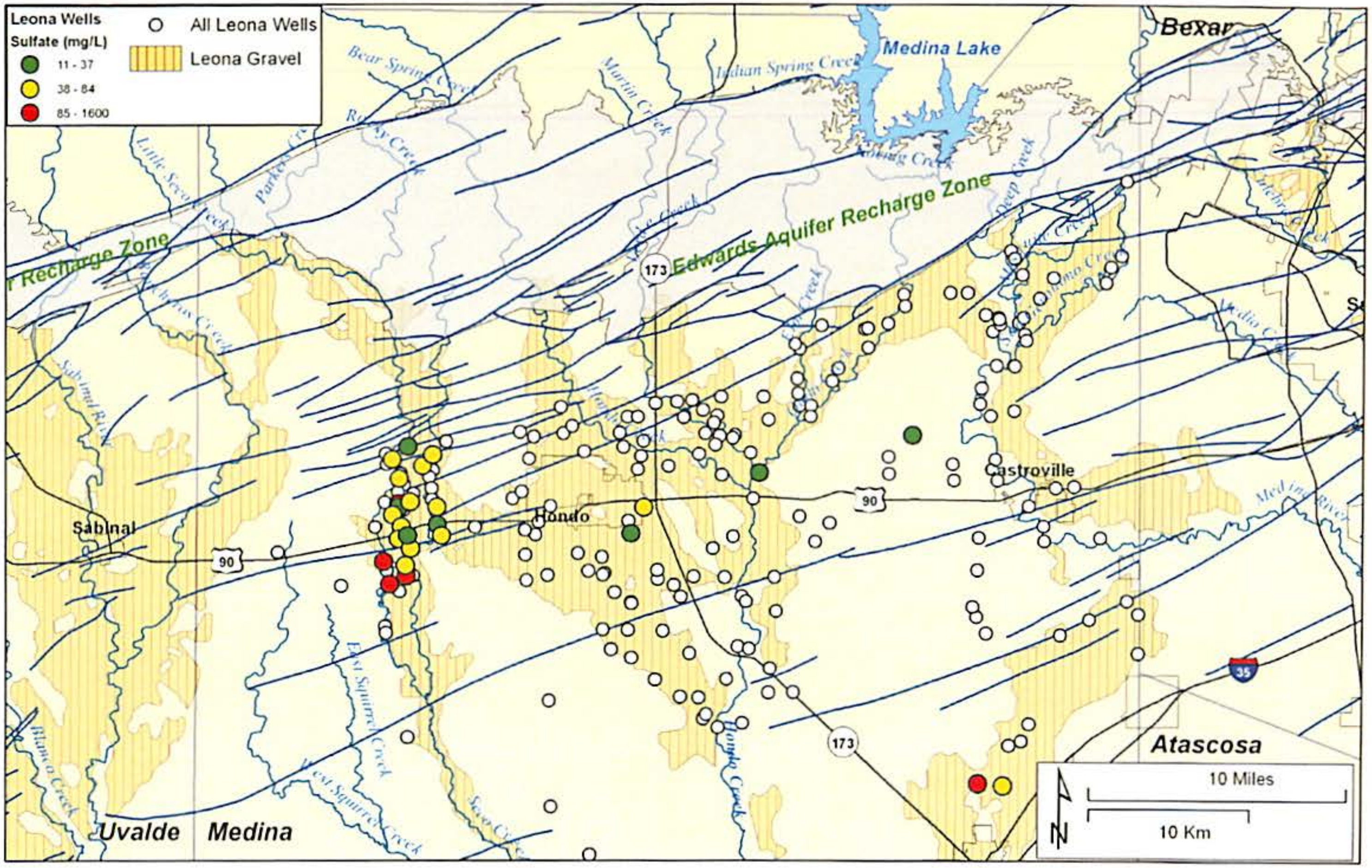

Figure 22: Map of Leona Formation wells with (color) and without (white) available water chemistry data in the Texas Water Development Board (2011) database. Major faults are denoted by blue lines.

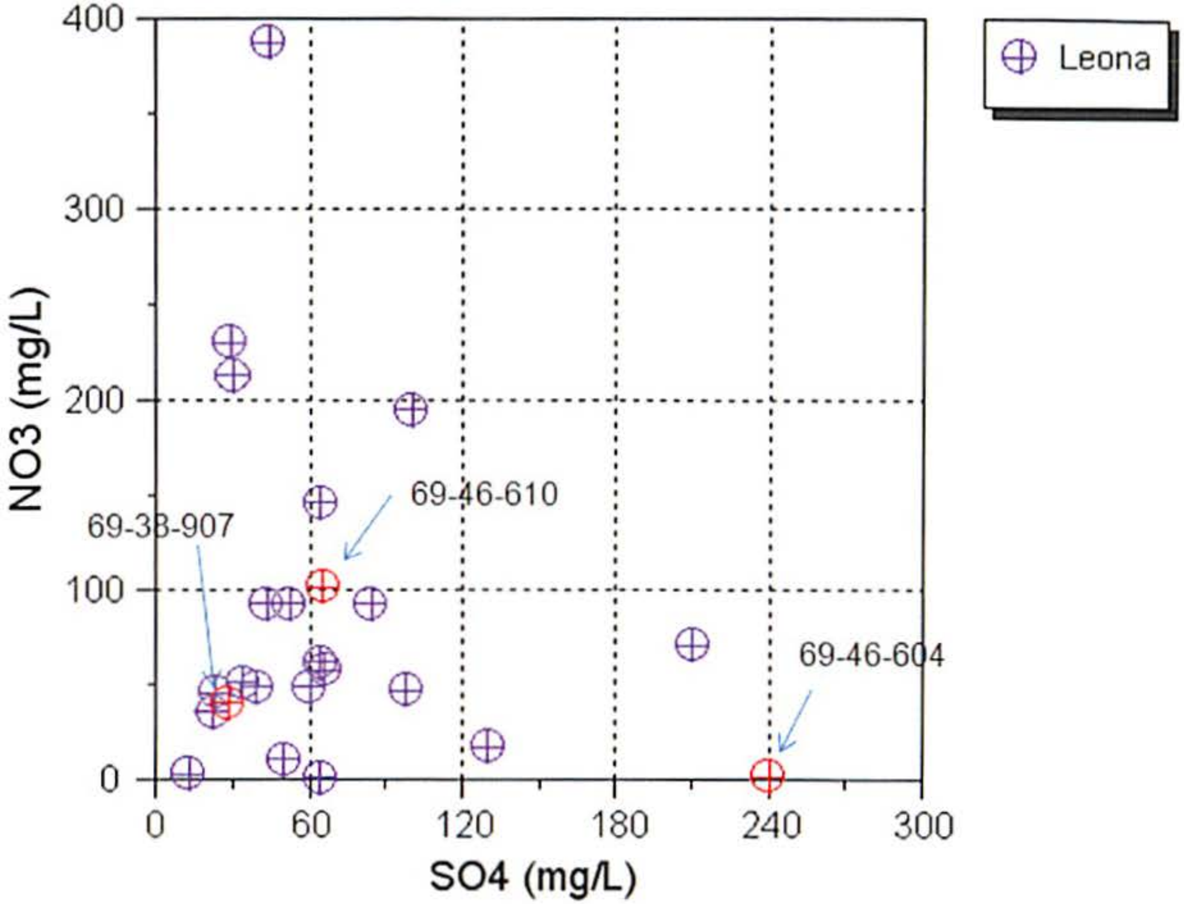

Figure 23: Plot of nitrate and sulfate concentrations for Leona Formation wells in Medina County. Wells highlighted in red are discussed in Section 6.1.

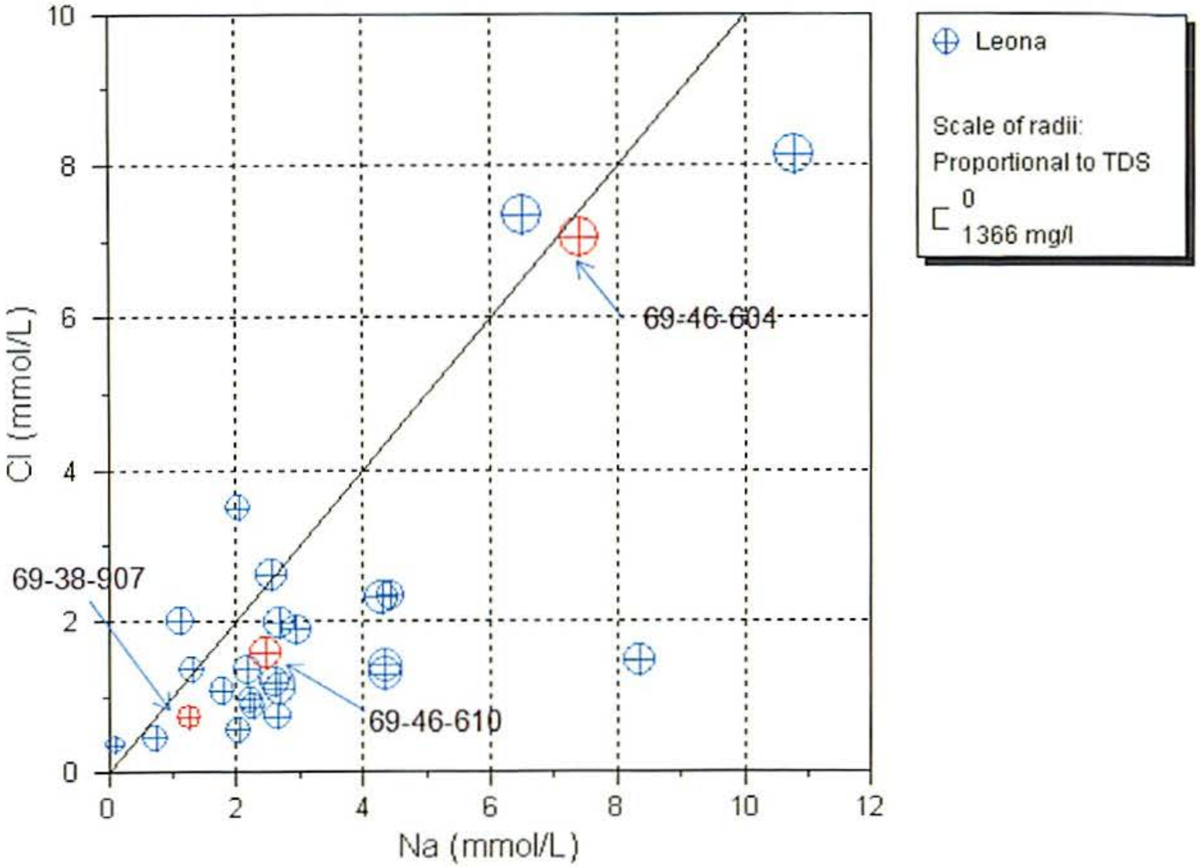

Figure 24: Plot of sodium and chloride Concentrations for Leona Formation wells in Medina County. Wells highlighted in red are discussed in Section 6.1 of the text. The size of the data points is proportional to total dissolved solids concentration for the well.

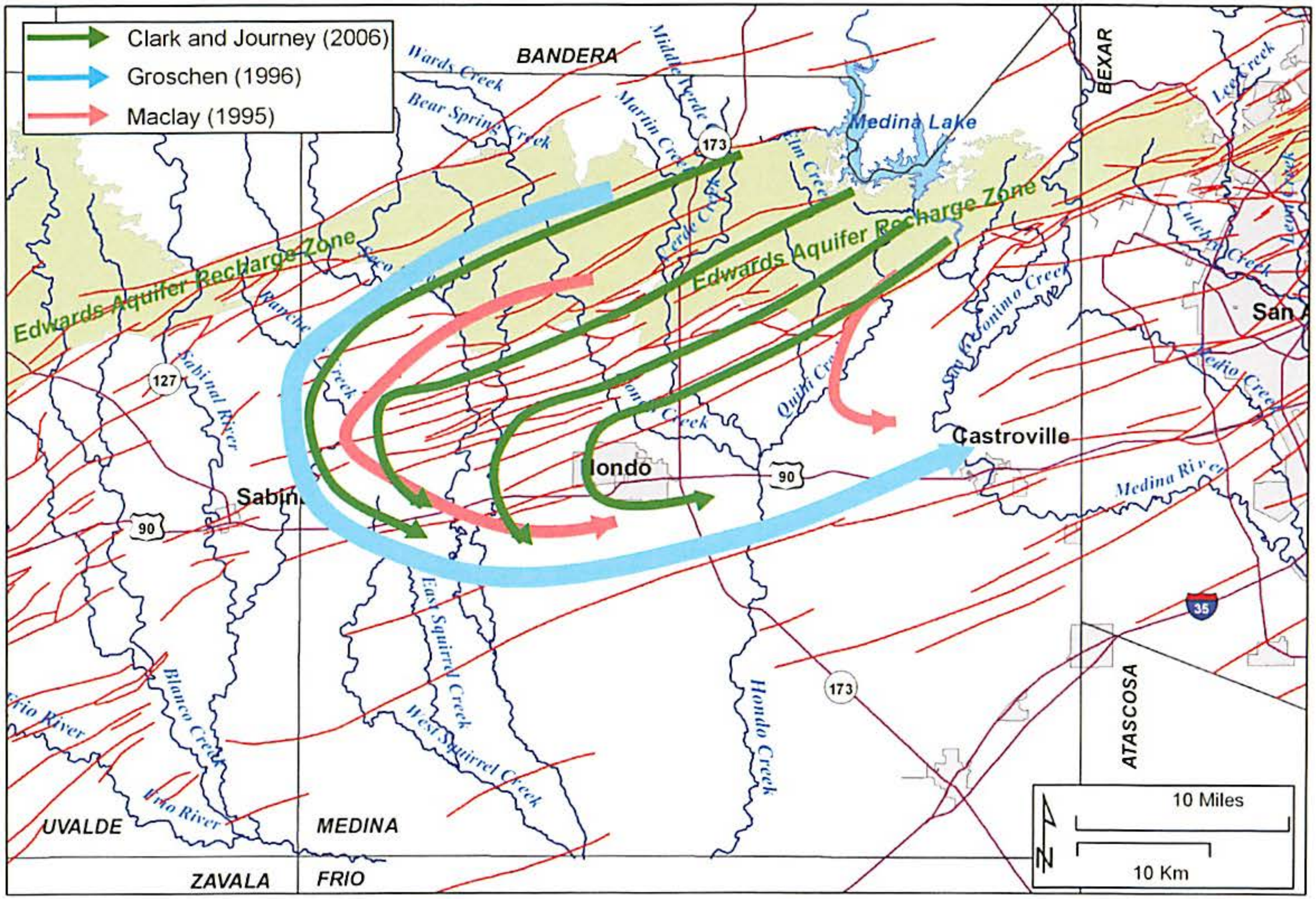

Figure 25: Approximate locations of Medina County Edwards Aquifer flowpaths proposed by previous investigators. Major faults are denoted by red lines.

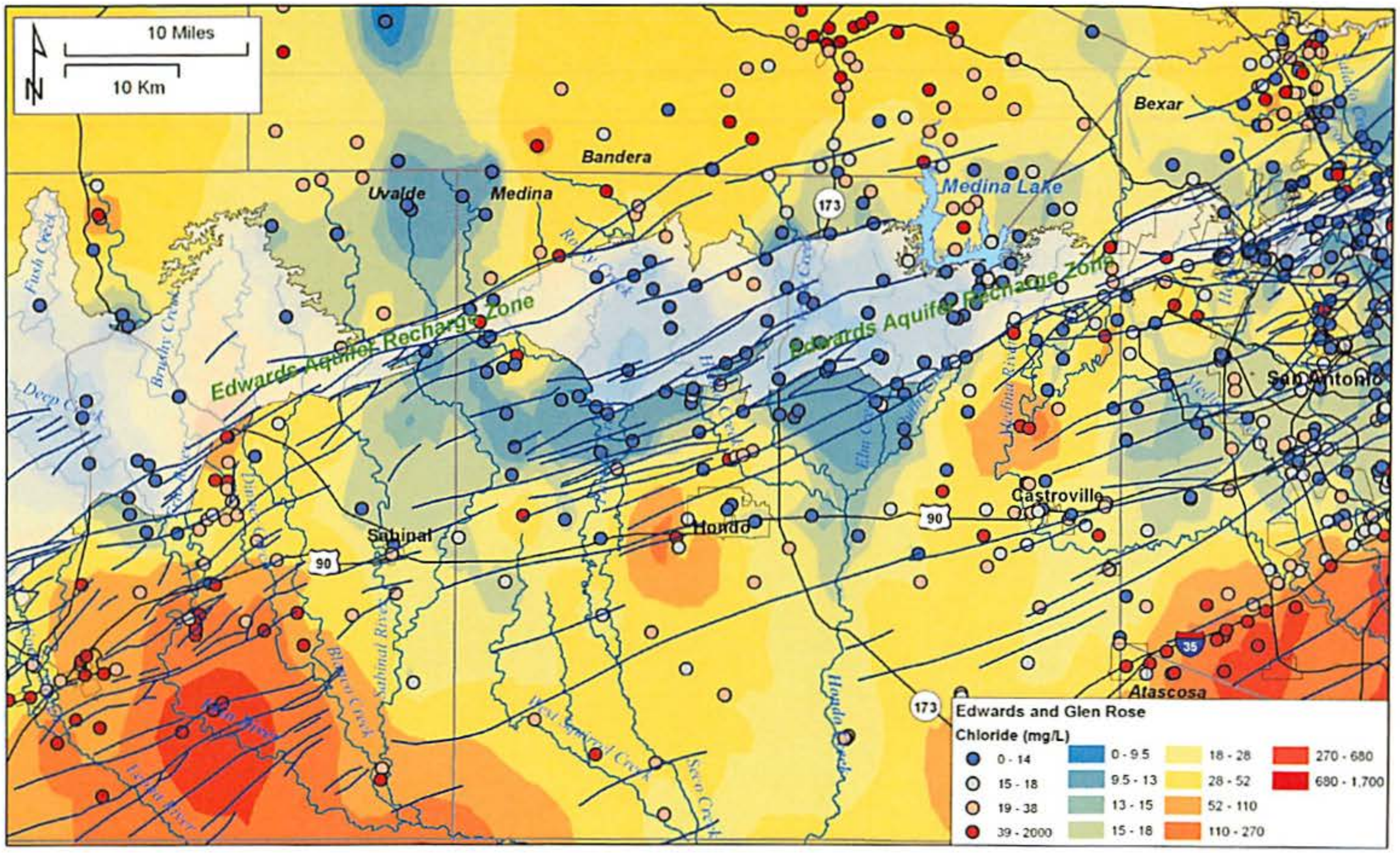

Figure 26: Map of chloride concentrations for Edwards and Trinity Aquifer wells. Concentration contours are prediction maps based on available data and are not constrained by faults. Major faults are denoted by blue lines.

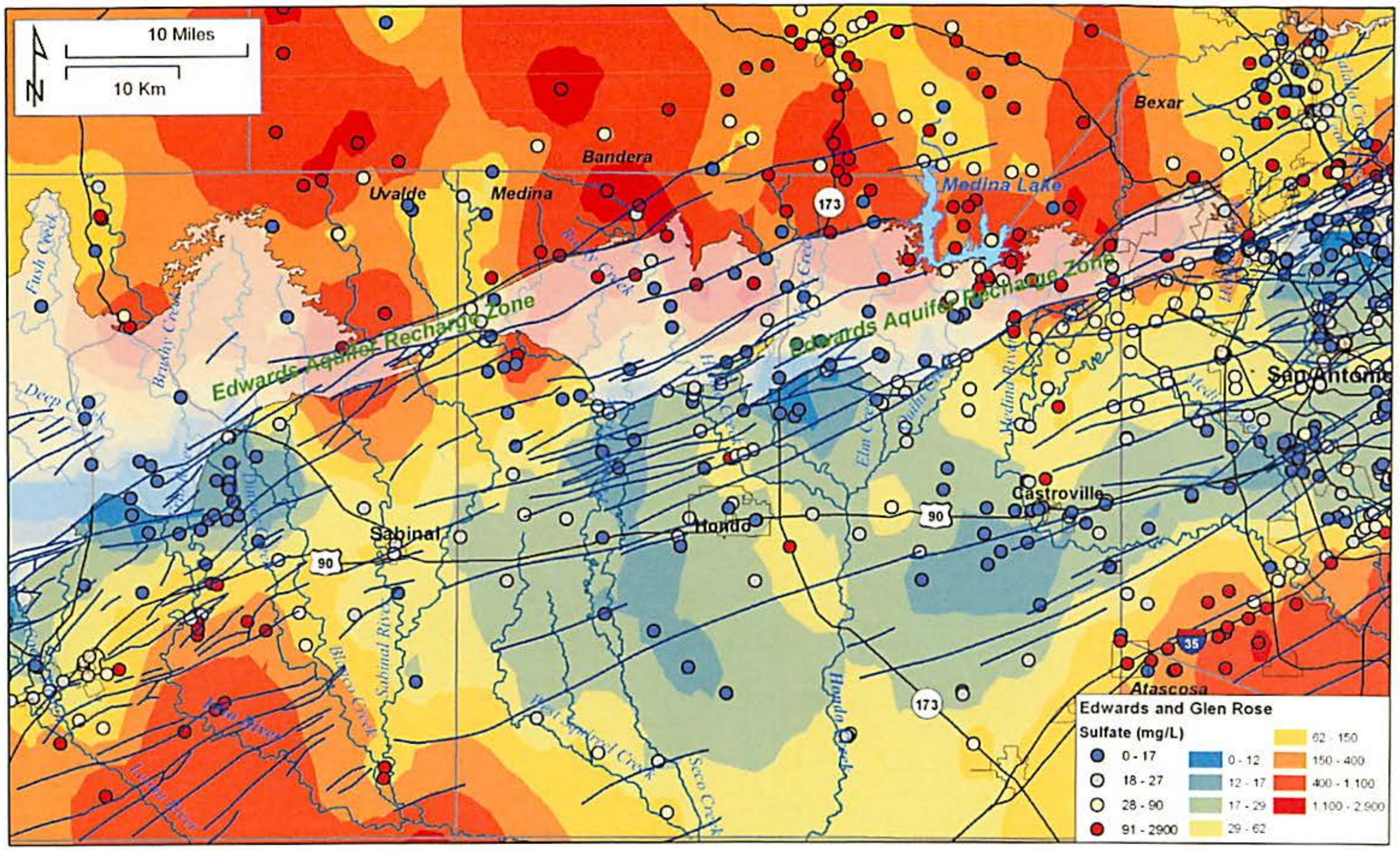

Figure 27: Map of sulfate concentration for Edwards and Trinity Aquifer wells. Concentration contours are prediction maps based on available data and are not constrained by faults. Major faults are denoted by blue lines.

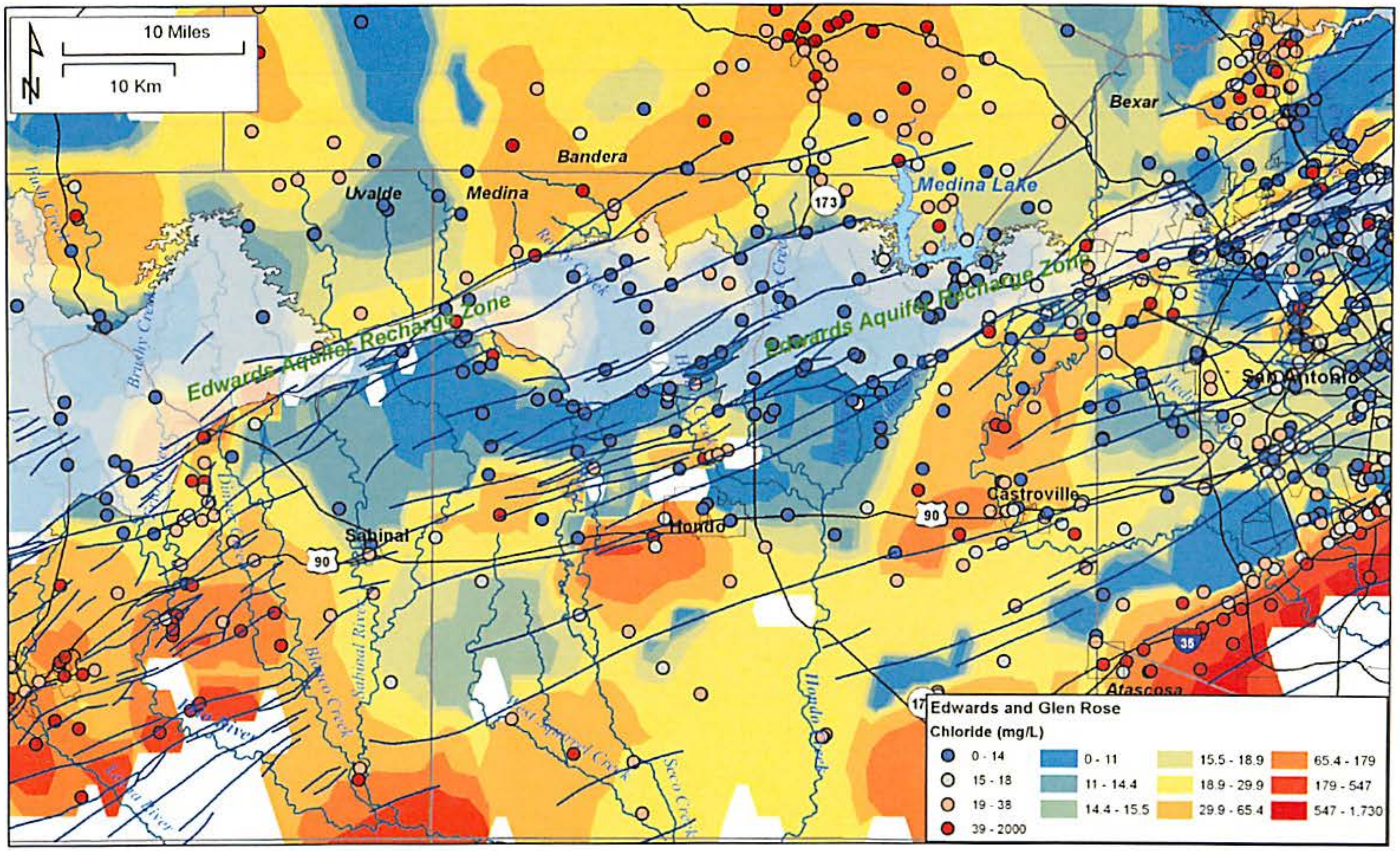

Figure 28: Map of chloride concentrations for Edwards and Trinity Aquifer wells. Concentration contours are prediction maps based on available data and are constrained by modeling all shown faults as barriers. White areas indicate model instability and no solution is plotted for those locations. Major faults are denoted by blue lines.

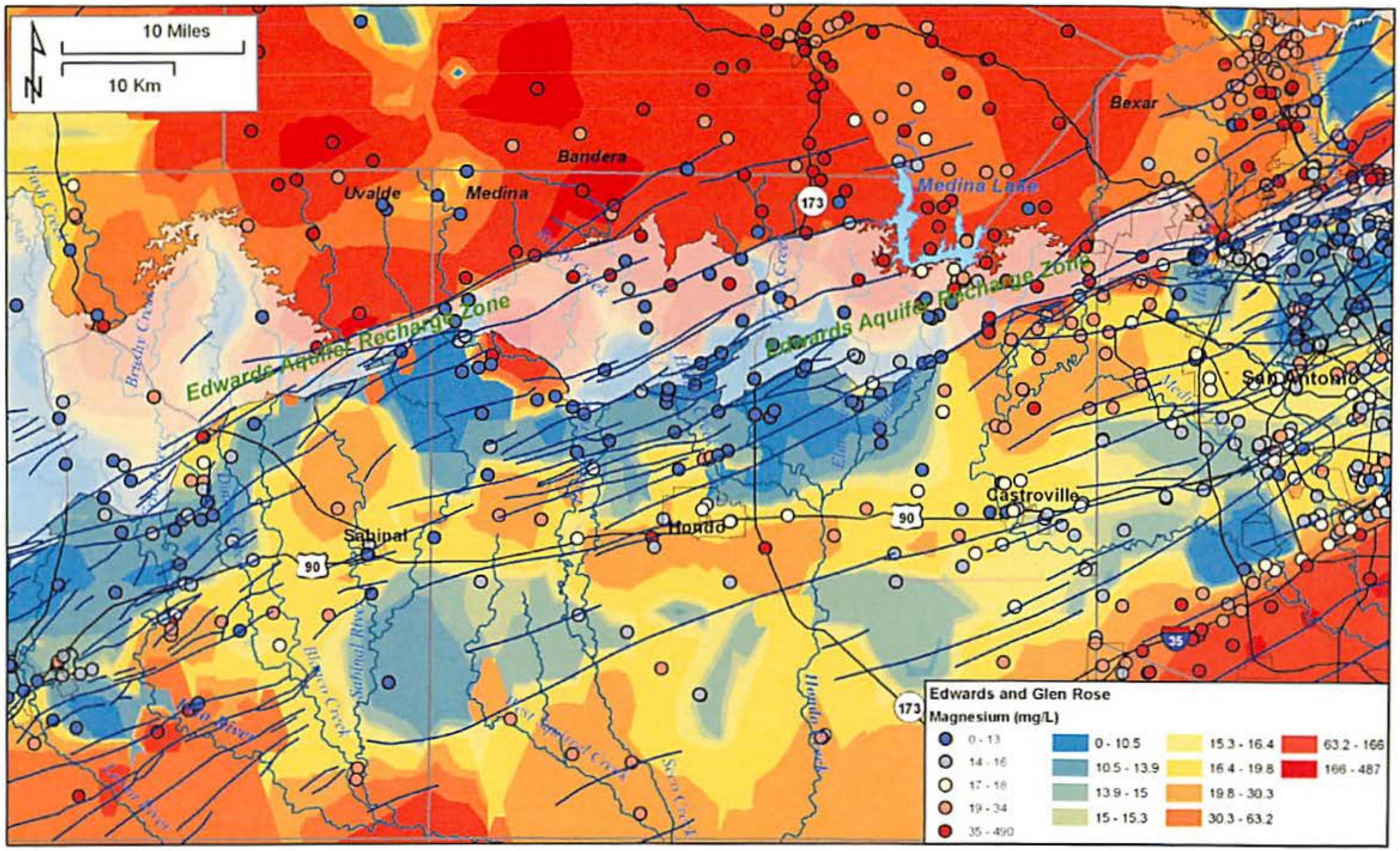

Figure 29: Map of magnesium concentrations for Edwards and Trinity Aquifer wells. Concentration contours are prediction maps based on available data and are constrained by modeling all shown faults as barriers. Major faults are denoted by blue lines.

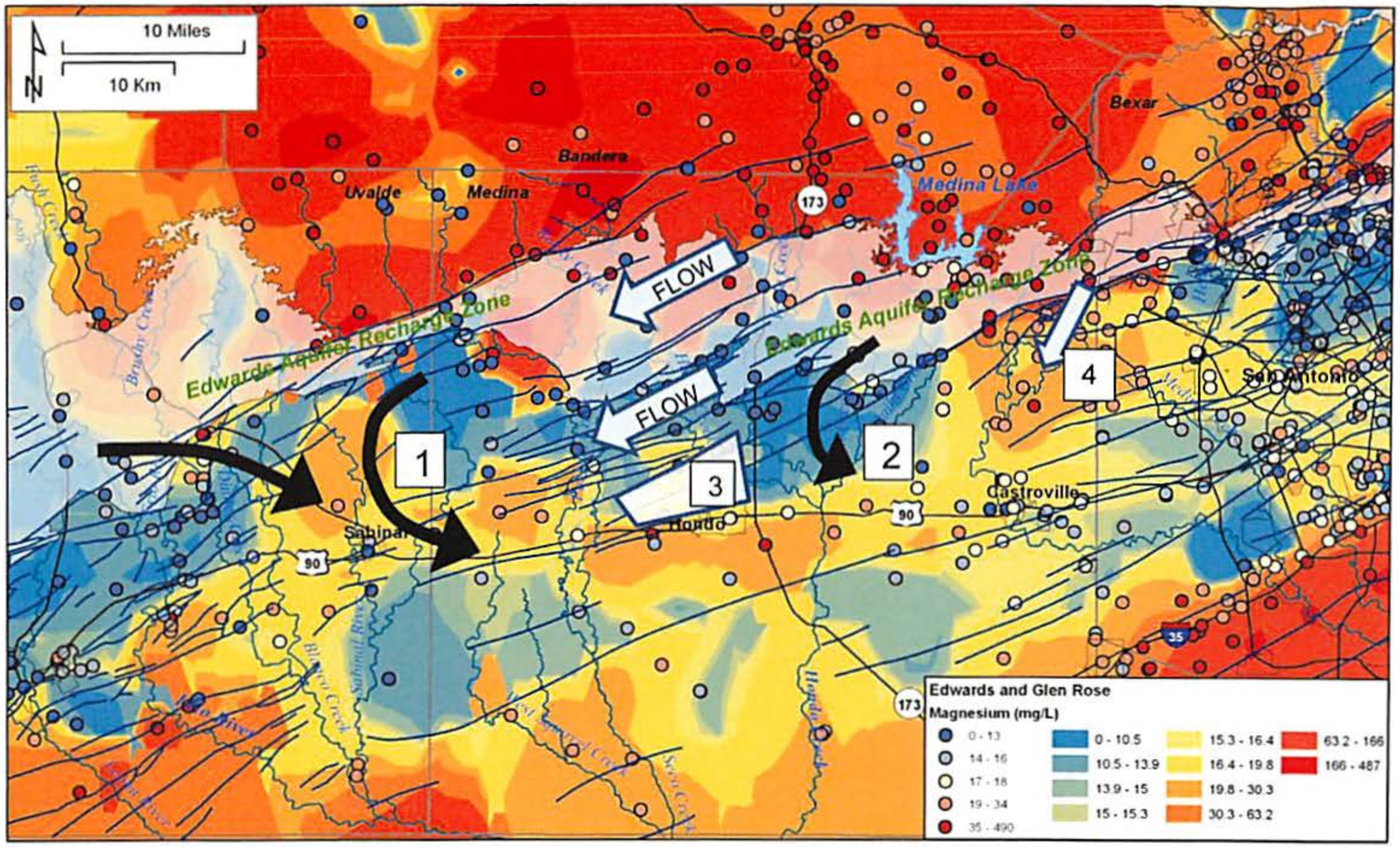

Figure 30: Map of magnesium concentrations for Edwards and Trinity Aquifer wells. Concentration contours are constrained by modeling all shown faults as barriers. Map depicts proposed flowpaths based on hydrochemical analyses. See Section 6.2 for discussion. Major faults are denoted by blue lines.

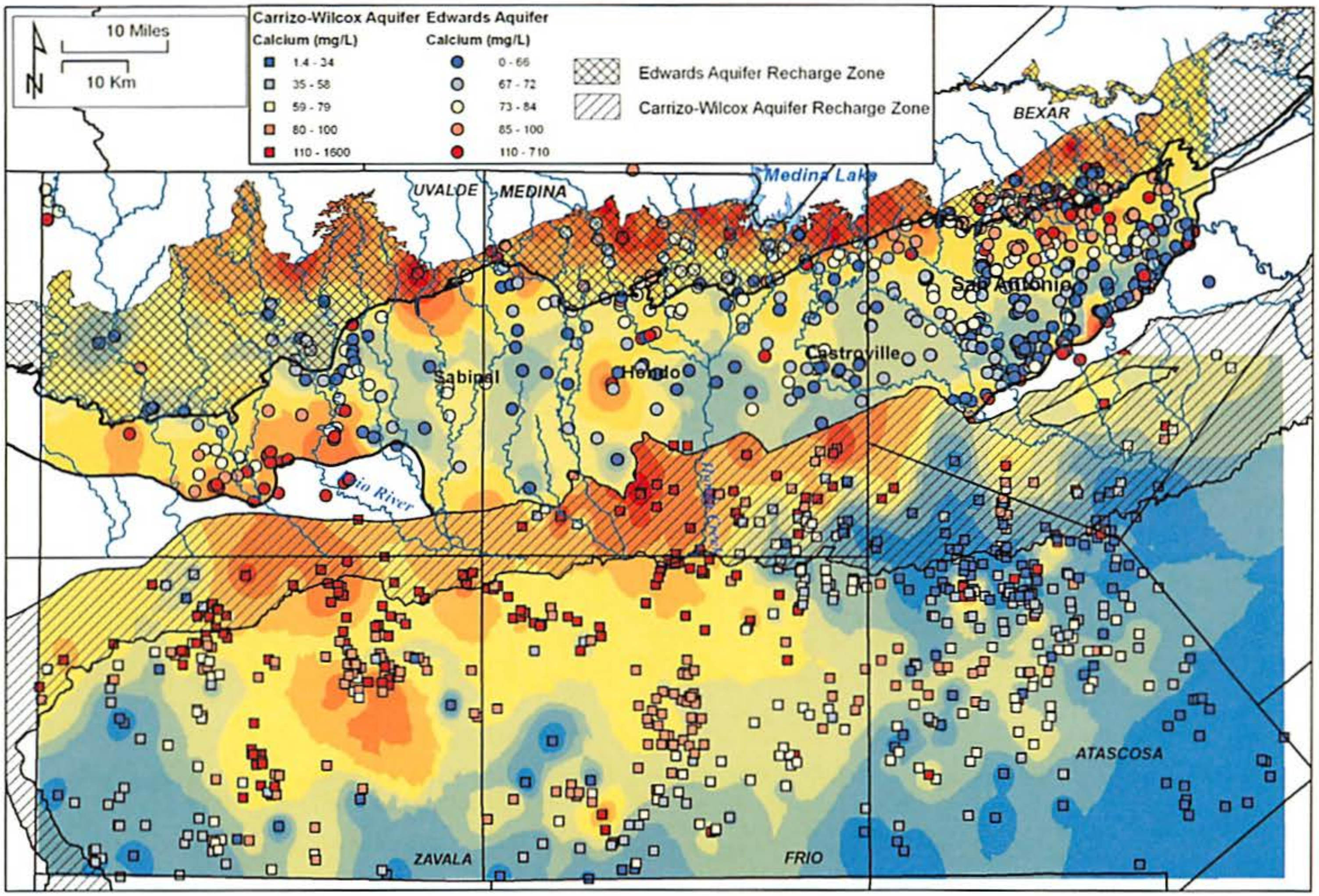

Figure 31: Overlay map of calcium concentrations in the Edwards and Carrizo-Wilcox aquifers. Contours represent inverse distance weighted geostatistical prediction maps of calcium concentrations in each aquifer and are based on the available data.

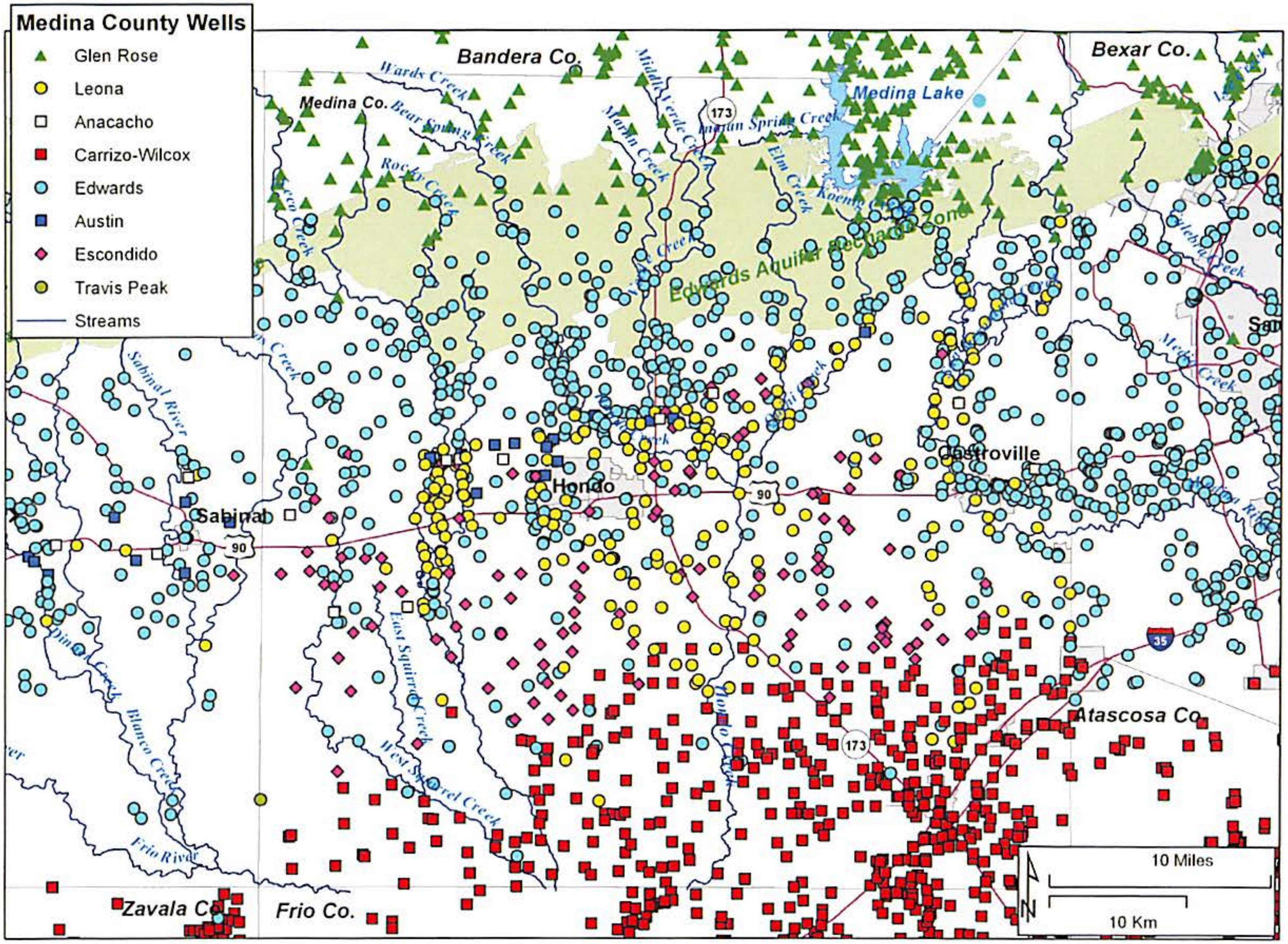

Figure 32: Map of wells in Medina County According to their aquifer designation in the Texas Water Development Board (2011) database.