GEOPHYSICAL SURVEY TO DETERMINE THE DEPTH AND LATERAL EXTENT OF THE LEONA AQUIFER AND EVALUATION OF DISCHARGE THROUGH THE LEONA RIVER FLOODPLAIN, SOUTH OF UVALDE, TEXAS

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Introduction

Accurate assessment and management of the groundwater resources of the Edwards aquifer require that major sources of water recharge into and discharge from the aquifer be adequately determined. Of interest in this investigation is discharge from the Edwards aquifer as surface water or groundwater flow through the Leona River channel which crosses the aquifer. River channel discharge from the aquifer will only occur in places where the Edwards aquifer is unconfined, no significant thicknesses of impermeable materials separate the river channel from the aquifer, and the static level of groundwater in the Edwards aquifer is higher than the base of the river channel surface or higher than the surface of groundwater flow in the floodplain aquifer.

River channels such as those of the Nueces or Frio Rivers (Figure 1) which cross the Edwards aquifer west and east of the Leona River, respectively, do not have sufficient floodplain sediments for a significant fluvial aquifer. Among these river channels, discharge from the Edwards Aquifer is limited to possible surface (or minimal shallow subsurface) water flowing through the river channel. Water recharge into or discharge from the Edwards Aquifer via rivers such as the Frio and Nueces is determined by calculating gains or losses along a reach of the river using stage and flow measurements.

The Leona River floodplain differs from those of the Frio and Nueces Rivers. The Leona River floodplain consists of relatively thick (i.e., as great as 70-80 ft) sediments that span a width as great as three miles in places. The sediments, part of the Leona Formation, contain significant sand and gravel paleo-streambed deposits that form the Leona aquifer, which can be a locally prolific aquifer. The potential high capacity for groundwater flow may make the Leona River floodplain a significant area of discharge from the Edwards Aquifer. To determine the quantity of groundwater flow through the Leona aquifer, the depth, lateral extent, hydraulic properties, and groundwater gradient must be known or at least reasonably estimated.

A dipole-dipole resistivity survey was conducted in March 2003 to determine the depth and lateral extent of the sand and gravel deposits in the Leona River floodplain. This information was combined with borehole logs, a potentiometric map of groundwater, and the results from a 10-day aquifer test to determine the groundwater flow regime of the Leona Formation aquifer in the Leona River floodplain. The groundwater flow regime was used, in turn, to constrain a conceptual model for groundwater flow through the Knippa Gap portion of the Edwards Aquifer.

Background

The Leona Formation forms the Leona River floodplain and consists of stratified gravels, sands, and clays eroded from the Edwards Plateau. The clays were deposited in a low energy environment and represent the less permeable sections (aquitard) of the Leona Formation. Conversely, the sands and gravels were deposited in a high energy environment and formed the fluvial Leona aquifer. Locally, the Leona aquifer can be a prolific water source as demonstrated by wells with sustainable capacities in excess of 1200 gpm. On the other hand, wells at other locations in the Leona River floodplain, occasionally in close proximity with the high producing wells, produce significantly less water (i.e., less than 100 gpm). This extreme spatial variability reflects the fluvial depositional environment of the Leona Formation which is characterized by laterally discontinuous channel fill sequences and over bank deposits with variable thickness.

The Uvalde area has experienced a complicated and complex history of faulting (Clark and Small, 1997; Clark, 2003). In general, the faults are consistent with the regional fault orientations in the Balcones fault system strike. Although the Edwards aquifer strata are exposed at the surface in Uvalde, normal faulting places the top of the Edwards at a depth of 400 ft in the vicinity of this field investigation.

The headwaters for the Leona River are located near the center of Uvalde, except during periods of extreme drought (when the river is dry in Uvalde) or heavy precipitation (when river flow is experienced north of the city center). Based on the geologic structural interpretation by Clark and Small (1997) and Clark (2003), the Leona Formation is juxtaposed with the Edwards Formation at the location of the Leona River headwaters providing a source of surface and groundwater for the Leona River floodplain. South of Uvalde, along the Leona River, normal faulting has displaced the Edwards Formation to greater depths, separating it from the Leona Formation first by the Del Rio Clay and then by the Buda Formation and the Eagle Ford Shale. The combined thickness of the clay-rich basal unit of the Leona Formation, Eagle Ford Shale, Buda Formation, and Del Rio Clay provide over 300 ft of separation between the sand and gravel aquifer of the Leona Formation and the Edwards aquifer at the site of this investigation. Additional normal faulting to the south increases this separation in the southern reaches of the Leona River floodplain. The hydraulic barrier resulting from this separation, and the fact that the Leona floodplain is displaced from areas where the Edwards aquifer strata are exposed at the surface, support the premise that surface and groundwater that has reached the survey site (Figure 1) 4.5 miles south of Uvalde can be considered as discharge from the Edwards Aquifer.

Welder and Reeves (1962) assert that the gravel portion of the Leona Formation is as great as 35 ft thick and 10,000 ft wide in the Leona River floodplain. They further assert that the gravel aquifer is thickest near the center of the floodplain and thins near the edges of the valley forming the floodplain. These assertions were based on observations that the most prolific Leona aquifer wells tended to be located near the center of the floodplain and that wells near the edges do not provide significant, sustainable sources of groundwater.

Survey Description

The site for the Leona River floodplain resistivity survey, located approximately 4.5 miles south of Uvalde, Texas (Figure 2), was selected because: (i) the lateral extent of the Leona River channel is relatively well defined to the east by the Taylor Hills and to the west by the unnamed hills west of Highway 117; (ii) the hydraulic properties of the Leona aquifer have been well characterized by an aquifer pump test conducted near the middle of the floodplain; and (iii) a USGS stream gauge is located near the resistivity survey transects which cross the Leona River floodplain. Subsequent to conducting the resistivity survey, a water well was installed along one of the survey transects located west of the Leona River (well LMW1 in Figure 2). The drillers logs from the newly drilled borehole and from several existing wells located east of the Leona River offer the opportunity to compare the relative electrical measurements of the resistivity survey with specific properties of the Leona Formation. Integration of these data, in conjunction with the physical dimensions of the Leona aquifer determined using results from the resistivity survey, allows for a reasonable estimate of the combined surface and groundwater flow through the Leona River floodplain.

The resistivity survey consists of five individual transect segments covering a distance of 3 miles across the Leona River floodplain. A single 3-mile long transect was not possible due to inaccessibility of contiguous properties across the entire floodplain. Additional inaccessibility resulted from excessive vegetative coverage and paved roads. The five separate, east-west trending transects are identified as UVAL4, UVAL5, UVAL6, UVAL7, and UVAL8 in Figure 2. Graphical interpretations of the transect segments are integrated to form a single interpretation that spans most of the Leona River floodplain.

Resistivity measurements along the five transects were collected with an AGI R8 SuperSting™ resistivity system using a continuous "roll-along" survey method to provide continuous coverage along each transect. The measured data were rigorously inverted using the L_1 norm to provide an interpretation of the subsurface (Loke, 2000, 2001).

Resistivity Survey Results

Results for each resistivity transect are graphically illustrated as vertical profiles in Figure 3. As illustrated, the transects provide an interpretation to a depth of slightly more than 100 ft, a depth greater than the base of the Leona aquifer in this section of the Leona River floodplain. The resistivity survey results are interpreted by associating sands and gravels with high resistivity and silts and clays with low resistivity. In particular, the relatively low resistivity areas (blue and green colors) in the vertical sections (Figure 3) are interpreted as the low permeable aquitard portions of the Leona Formation. The more resistive areas (yellow through purple colors) are interpreted as the sands and gravel of the Leona aquifer. The less resistive areas (blue and green colors) below the sands and gravels are interpreted to be the basal clay-rich unit of the Leona Formation. There was no indication of additional sand and gravel units below the basal clay-rich unit to an approximate depth of 85 ft.

Transitions from the finer-grained overburden to the sand and gravel deposit and from the sand and gravel deposit to the underlying clay-rich unit are determined, in part, using the lithologic log of the borehole located at the 500 ft distance mark along the UVAL5 resistivity transect (LMW1 in Figure 3B). The borehole was drilled in October 2003. The lithologic log was taken by a driller and not a geologist; therefore, the material characteristics are descriptive only. In addition, the driller estimated the potential capacity of the water well at 300 to 500 gpm, which, although significant, is less than many Leona aquifer wells that produce in excess of 1,000 gpm. This observation suggests that the well was not set in one of the more productive sections of the Leona River floodplain. The descriptive log for the borehole is presented in Table 1.

Table 1. Geologic log for a borehole (LMW1 in Figure 2) located at the 500 ft mark on resistivity transect UVAL5. (E. Franke, personal communication).

Depth (ft)	Material
0 – 5	Surface
5 – 10	Red clay
10 – 30	Tan clay
30 – 40	Caliche
40 – 45	Caliche and flint rock mix
45 – 47	Hard cemented flint rock
47 – 60	Soft flint rock and clay
60 – 62	Gravel
62 – 65	Yellow clay
65 - 70	Blue clay

The driller log suggests that the aquifer portion of the Leona Formation is limited to a 2-ft thick section at a depth of 60 to 62 ft below ground level (bgl). A comparison of the resistivity profile with the borehole log suggests a correlation of about 100-150 ohm-m with the transition from the silt/clay to the sand/gravel of the Leona aquifer. This range of values of resistivity includes values greater than typically attributed to clays. In addition, resistivity profile UVAL5 (Figure 3B) indicates a zone of high resistivity beginning at a depth of about 30 ft bgl at the location of the well and continuing to a depth of 70 to 80 ft for a thickness as great as 40 ft. If this zone of high resistivity is associated with the sand and gravel unit, there is an inconsistency between the driller's log and the resistivity profile. The inconsistency may be attributed to several sources. Two-dimensional resistivity profiles measure a volume of the subsurface greater than the subsurface immediately below the transect. The braided-stream nature of the paleo-river that formed the sand and gravel deposits of the Leona aquifer may have resulted in the borehole not penetrating the sand- and gravel-rich deposit detected by the resistivity survey. This effect may have been exacerbated if the borehole was not placed by the driller exactly along the resistivity transect in which case the descriptive borehole log does not accurately represent the formation along the transect. Lastly, the relatively limited thickness of the aquifer is not fully consistent for a well with a capacity estimated by the driller to be 300 to 500 gpm (E. Franke, personal communication). Because of these inconsistencies, the descriptive borehole log cannot be heavily relied on for corroborative evidence.

Driller logs from existing wells located east of the Leona River provide additional evidence that the sand- and gravel deposits meander significantly through the floodplain and that the resistivity transition from silt/clay to sand/gravel is less than 100-150 ohm-m. Driller logs are available for three wells (LMW2, LMW3, and LMW4) located near, but not on, the resistivity transect located east of the Leona River (UVAL4). The wells are offset 200 to 500 ft southeast of the transect. Because all three wells are high producers (i.e., greater than 1,000 gpm), they are obviously located in sections of the floodplain with a significant thickness of sand and gravel. When projected onto transect UVAL4, the wells are located at the 600 (LMW2), 800 (LMW3), and 1800 (LMW4) ft distances. Another well (LMW7) located at 3600 ft on UVAL4 has no borehole log, but is known to have high productivity (i.e., greater than 1000 gpm). This high water productivity indicates significant sands and gravels at this location. The Leona aquifer is estimated from the logs to be at depths of 32-65 ft bgl (LMW2), 28-55 ft bgl (LMW3), and 30-58 ft bgl (LMW4). Comparison of the these gravel deposits with resistivity transect UVAL4 suggests that the transition from the silt/clays to the Leona aquifer correlates with a resistivity of about 20-30 ohm-m, significantly less than the correlation of 100-150 ohm-m inferred from the borehole log on UVAL5.

Another resistivity survey conducted at a similar geologic setting provides useful information for interpreting the Leona River floodplain resistivity survey. This survey consisted of five resistivity transects from the floodplain of the Colorado River near Columbus, TX (proprietary project for Raba-Kistner Consultants, Inc., San Antonio, Texas). The survey results are of interest because each transect was interpreted with lithologic logs for three drillhole borings which allowed for less uncertainty when correlating sand and gravel deposits with resistivity values. The five parallel transects were approximately 1800 ft long and separated by 1200 ft. Even though the sediments were continuous across the survey site, resistivity values associated with the transition from clay to sand and gravel varied from as low as 30-45 ohm-m in transects where the sand and gravel content was moderate to 75-85 ohm-m in transects where the sand and gravel content was significant. The variability in resistivity values may be a consequence of a greater gravel fraction in the sand and gravel unit or simply attributed to equivalence in the inversion routine.

Resistivity transects and well logs to the east of the Leona River suggest that the transition from silt/clay to sand/gravel in the Leona River floodplain is less than that estimated for the Colorado River floodplain. The transition from silt/clay to sand/gravel is estimated to occur at approximately 25 to 50 ohm-m in the Leona River floodplain compared with 30-85 ohm-m at the Colorado River floodplain site. The difference in the electrical properties may be attributed to mineralogical differences in the geologic source material for the sediments or the chemical nature of the formation water, either of which could influence the composite electrical properties. The geologic source area for both floodplains is the Cretaceous limestones from the Texas Hill Country, therefore the mineralogical composition of the sediments does not appear to be a first-order cause for changes in resistivity measurements.

Measurements of water sampled from both sites suggest that differences in the electrical properties of the formation water are a more likely source for the discrepancy in resistivity transition values from silt/clay to sand/gravel. Specific conductance values for water from the Leona Formation (i.e., 1,000 to 1,200 μmho/cm) are slightly less than double the specific conductivity value for water from Colorado River floodplain fluvial aquifers (600 to 650 μmoho/cm)(Texas Water Development Board Water Information Integration and Dissemination System).

Archie's empirical formula relates the composite resistivity of a medium to the resistivity of the formation water as follows (Telford et al., 1978)

$$\rho_e = a\phi^{-m}s^{-n}\rho_w$$

where ρ_e is the bulk resistivity of the formation, ρ_w is the resistivity of the water, ϕ is porosity, s is saturation, and n, a, and m are constants such that $0.5 \le a \le 2.5$ and $1.3 \le m \le 2.5$. Full saturation of the sands and gravels at both sites is assumed, therefore Archie's formula simplifies slightly. The *m* coefficient represents the degree of cementation of the medium. In general, unconsolidated media have a lower value and consolidated media have a higher value of *m*. Because media at both sites are unconsolidated materials and the source areas for both are Cretaceous limestones from the Texas Hill Country, it is assumed that both have comparable values of *m*.

Based on Archie's formula, the formation resistivity is directly related to the water resistivity. This implies that the 30 to 85 ohm-m transition from silt/clay to sand/gravel observed at the Colorado River floodplain site corresponds to the approximate 25 to 50 ohm-m transition observed at the Leona River floodplain site. This relationship between the two sites is predicated on the assumptions that the geologic materials are sufficiently similar, that porosities and constants are equivalent, and that any difference in formation resistivity is attributed only to a change in the resistivity of the formation water.

Additional vertical cross sections have been constructed for the Leona River site in which only the 25 and 50 ohm-m contour lines for the five transects are illustrated (Figure 4). Based on the 25 an 50 ohm-m contour lines, the cross-sectional area of the sand and gravel deposit can be calculated for each vertical profile using Surfer 8™ software (Version 8.00). The calculated cross-sectional areas for each resistivity contour are summarized in Table 2. The larger value of 50 ohm-m results in a smaller cross-sectional area than the lower resistivity value. The total cross-sectional areas for the 25 and 50 ohm-m resistivity contours are 697,000 and 311,000 ft^2, respectively. If the Leona River floodplain is assumed to be 3 miles across with an average depth of 75 ft, then the floodplain has a total cross-sectional area of approximately 1.2 million ft^2. The aquifer therefore accounts for 25 to 58 percent of the floodplain.

Table 2. Cross-sectional areas of the Leona aquifer for each resistivity transect calculated using the Surfer 8™ software package. Areas are in ft^2.

Transect	Estimated area contained within 25 ohm-m contour	Estimated area contained within 50 ohm-m contour
UVAL4	226,000	85,000
UVAL5	125,000	60,000
UVAL6	78,000	22,000
UVAL7	164,000	97,000
UVAL8	104,000	47,000
Total area	697,000	311,000

Aquifer Test Results

A ten-day aquifer test was conducted near the Leona River and within 400 ft of resistivity transect UVAL4. Six wells in the Leona Formation (LMW2, LMW4, LMW5, LMW6, LMW7, and LMW8, Figure 5) and one in the Edwards Aquifer (EMW) were monitored during the five-day long pumping and five-day long recovery phases of the aquifer test in January 1998. An existing, 16-inch diameter irrigation well (LMW3) was pumped continuously at an average of 1,176 gpm for the duration of the pumping phase of the aquifer test. Groundwater drawdown and recovery data collected at the monitoring wells during the aquifer test provided a consistent assessment of the hydraulic properties of the Leona aquifer. The drawdown data were plotted in terms of feet versus time in log-log space for conventional Theis-curve analysis (Kruseman and De Ridder, 1983; Lohman, 1972, for example). Theis curves were matched to the log-log plots of drawdown data to determine transmissivity and storage. The groundwater recovery data were plotted in terms of residual drawdown versus dimensionless time (total time after the onset of pumping divided by time of recovery) in semi-log space (Kruseman and De Ridder, 1983) to determine transmissivity.

Values for transmissivity and storage calculated using the drawdown data and values for transmissivity only using the recovery data from the aquifer test are summarized in Table 3. As indicated, the transmissivity values range from a low of 80,000 ft^2/d at LMW5 to a high of 215,000 ft^2/d at the LMW6 observation well. This is a fairly narrow range for aquifer transmissivity, which indicates that flow properties between the pumped well and observation wells are similar. Values of the storage coefficient vary from a low of 0.00062 at LMW2 to a high of 0.05 at LMW5. This range of storage coefficients is indicative of confined or semi-confined aquifer conditions. Inherent in this analysis is the absence of a significant hydraulic connection between the Leona River and the Leona Formation along the reach of the Leona River at the study site as indicated by the observed drawdown at LMW6 and the absence of a recharge boundary in the semi-log drawdown plots.

Table 3. Summary of Leona River site aquifer test results

Well Number	Test Type	Transmissivity (ft^2/day)	Storage (-)	Aquifer Thickness (ft)	Hydraulic Conductivity (ft/day)
LMW2	drawdown	80,000	0.00062	33.0	2,425
LMW2	recovery	144,000	N/A	33.0	4,360
LMW4	drawdown	125,000	0.0048	28.0	4,460
LMW5	drawdown	140,000	0.020	18.0	7,780
LMW5	recovery	144,000	N/A	18.0	8,000
LMW6	drawdown	215,000	0.05	15.0	14,300

Not all well data collected during the aquifer test were conclusive. Insufficient drawdown was observed at LMW7 and LMW8 to provide for meaningful analysis. Recovery data collected at LMW8, LMW4, and LMW6 appear to be masked by pumping at an unidentified well during the recovery period and were not used in the analysis.

The direction of groundwater flow at the Leona River site was determined using groundwater elevations measured at LMW2, LMW3, LMW4, LMW5, LMW6, and LMW8 on January 23, 1998, five days after the termination of the aquifer test (Figure 5). As indicated by the analysis, the direction of groundwater flow follows the Leona River floodplain in a southeasterly direction. The gradient to groundwater flow in the study area was approximately 0.0023.

Surface Water Flow Measurements

Discharge in the Leona River has been measured by the USGS at the survey site since 1939. The measured discharge is plotted versus time in Figure 6. During this time, discharge has varied significantly, from a high of over 160 cfs in 1958 to periods of no river flow observed during the drought of the 1950's and on other occasions, most recently in 1996. Although highly variable, the average discharge in the Leona River at the survey site 4.5 miles south of the center of Uvalde is approximately 20 cfs.

Conclusions

An electrical resistivity survey was conducted on the Leona River floodplain to determine the lateral and vertical extent of the Leona aquifer at the survey site located 4.5 miles south of Uvalde, Texas. The resistivity survey results were used to determine the transition from the electrically conductive clay and silt portion of the floodplain sediments to the electrically resistive sands and gravel deposits which form the Leona aquifer. Some difficulty was encountered when assigning a specific electrical resistivity contour value to the transition from the silt/clay to sand/gravel sediments. This difficulty arose from the lack of accurate geologic logs for wells located near the resistivity transects. Additional insight as to the appropriate resistivity value to assign to the transition from silt/clay to sand/gravel was gained by using results from a comparable floodplain located along the Colorado River in south Texas. Specific conductance values for formation water were identified as a potential cause for slightly lower transition resistivity values at the Leona River site. Specific conductance values at the Leona River floodplain site were approximately double values taken at the Colorado River floodplain site. Based on the observation that the geologic source areas for both depositional sites are comparable and assuming all other coefficients in Archie's law are equal, indicates that the clay/silt to sand/gravel resistivity transition at the Colorado River site (i.e., 30 to 85 ohm-m) is approximately double the transition values at the Leona River site (i.e., 25-50 ohm-m). Consequently, the range of resistivity of 25 to 50 ohm-m that was assigned to the transition from silt/clay to sand/gravel in the Leona Formation appears reasonable. The corresponding cross-sectional areas associated with these resistivities are 697,000 and 311,000 ft^2, respectively. These areas account for 25 to 58 percent of the total cross-sectional area of the Leona River floodplain at the location of the resistivity survey.

The total groundwater discharge, *Q*, through the Leona river floodplain can be calculated using Darcy's Law (Freeze and Cherry, 1978)

$$Q = AK\nabla h$$

where *A* is the cross-sectional area, *K* is the average hydraulic conductivity, and ∇h is the hydraulic gradient of the Leona aquifer at the study site. For a cross-sectional area of 700,000 ft^2, hydraulic conductivity of 6,500 ft/day, and a gradient of 0.0023, the Leona River floodplain groundwater discharge is calculated to be 10,500,000 ft^3/day. This equates to approximately 120 cfs or 87,000 acre-ft per year. When combined with the average Leona River surface discharge of 20 cfs, the total water discharge from the Edwards aquifer via the Leona River floodplain is approximately 140 cfs (~100,000 acre-ft). Actual Leona River floodplain discharge is highly variable and depends on the water level in the aquifer and ultimately on climate conditions. Yearly rates may differ considerably from the average values. More accurate discharge can be determined by performing synoptic measurements of river discharge and groundwater elevations to reduce the uncertainty due to variability in both surface and groundwater flow regimes.

The USGS has estimated that approximately 120,000 acre-ft of water is recharged annually into the Edwards aquifer from the Nueces River (Hamilton et al., 2003) located west of Uvalde. Once recharged into the Edwards aquifer, groundwater eventually flows to the east through the Uvalde area. This investigation suggests that as much as 100,000 acre-ft of this water is discharged from the Edwards aquifer via the Leona River floodplain as a combination of surface flow through the Leona River and as groundwater through the Leona fluvial aquifer. Groundwater flow models used to manage the Edwards aquifer need to account for the potential loss of 100,000 acre-ft of this water as discharge via the Leona River floodplain.

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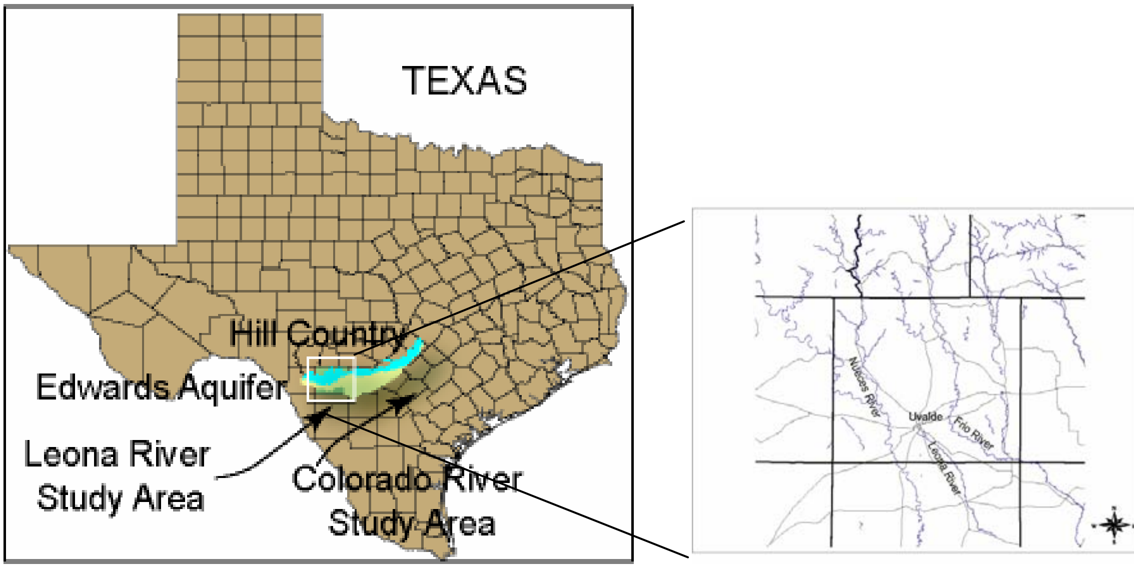

Figure 1. Geographical location of the investigation.

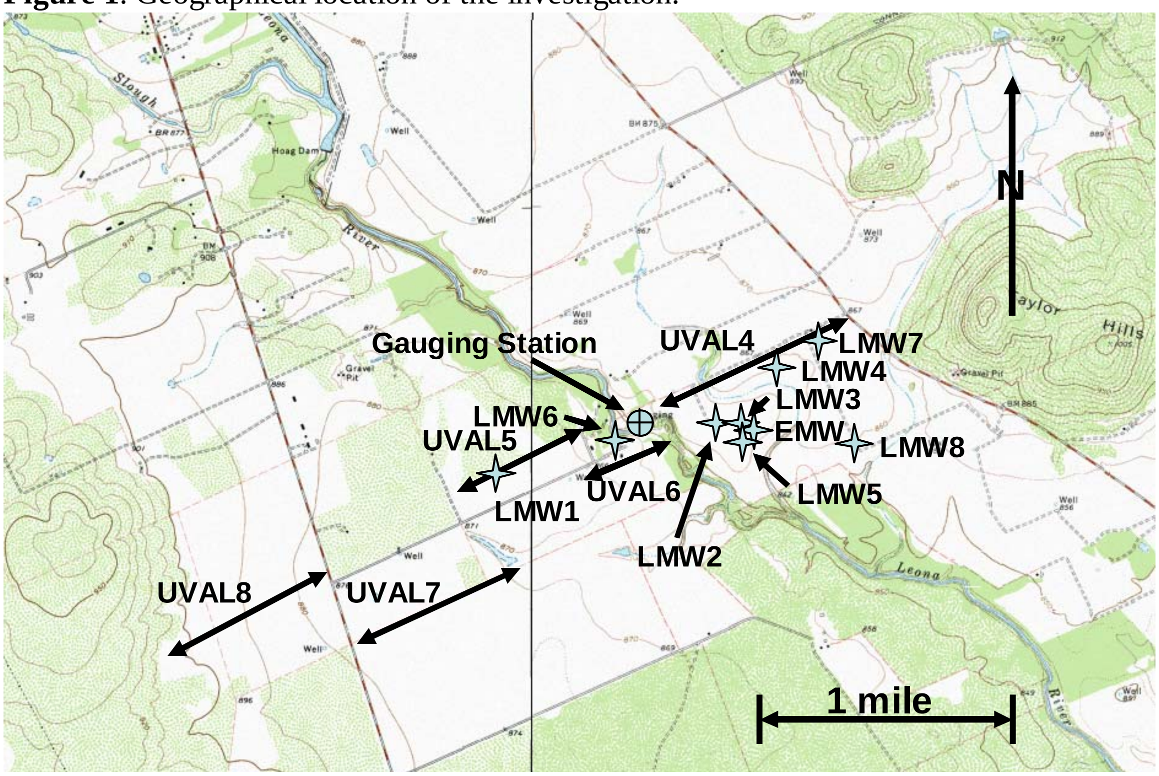

Figure 2. Survey location map, approximately 4.5 miles south of Uvalde. The five resistivity transects are designated as UVAL4, UVAL5, UVAL6, UVAL7, and UVAL8. The stars denote the four wells in the Leona Formation (LMW1, LMW2, LMW3, and LMW4) and the one well set in the Edwards Formation (EMW).

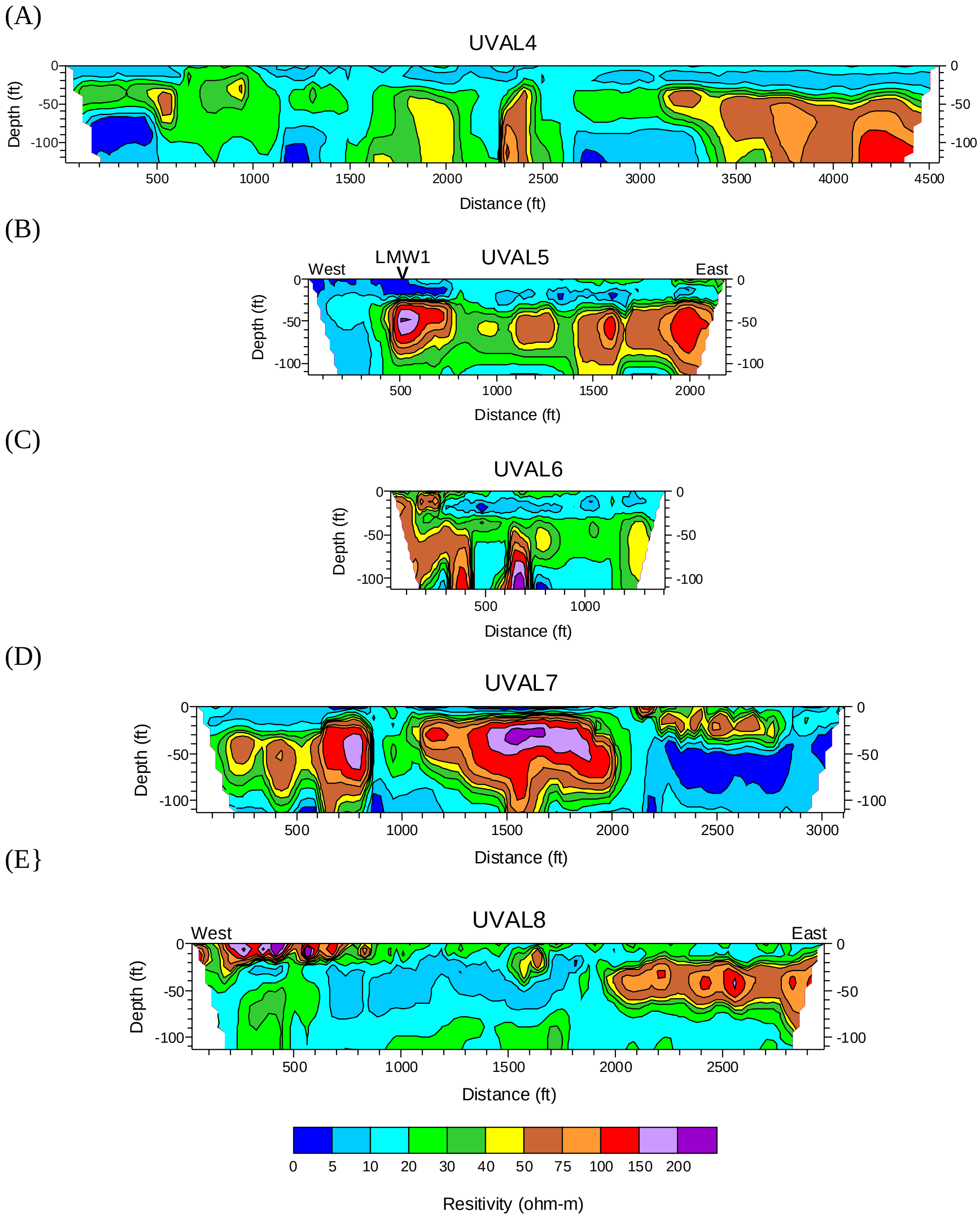

Figure 3. Vertical profiles of resistivity for transects (A) UVAL4, (B) UVAL5, (C) UVAL6, (D) UVAL7, and (E) UVAL8. Resistivity plotted in ohm-m.

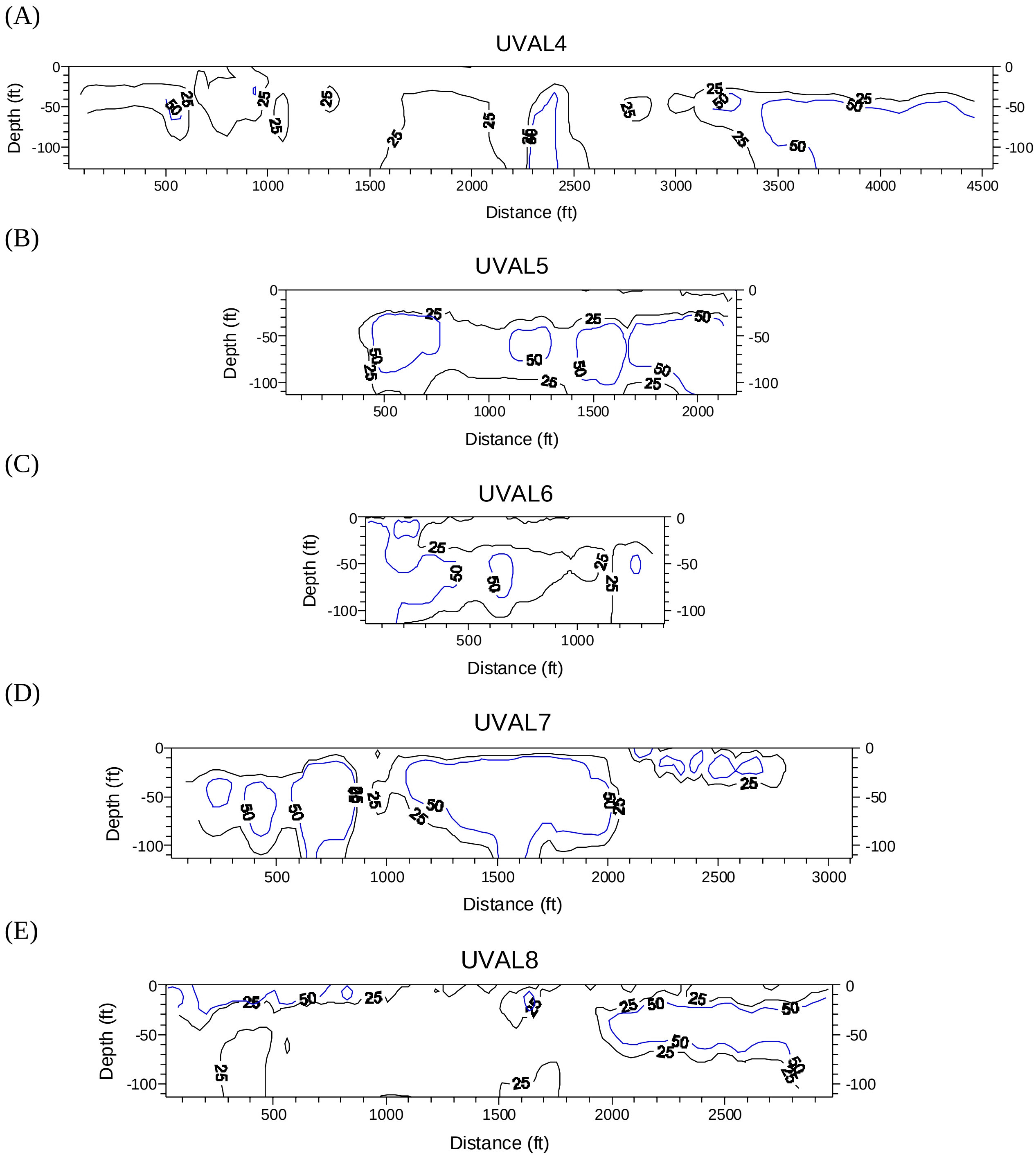

Figure 4. Vertical profiles of resistivity for transects (A) UVAL4, (B) UVAL5, (C) UVAL6, (D) UVAL7, and (E) UVAL8. The 25 and 50 ohm-m contour lines are included in the plot to illustrate the probable extent of the Leona sand and gravel aquifer.

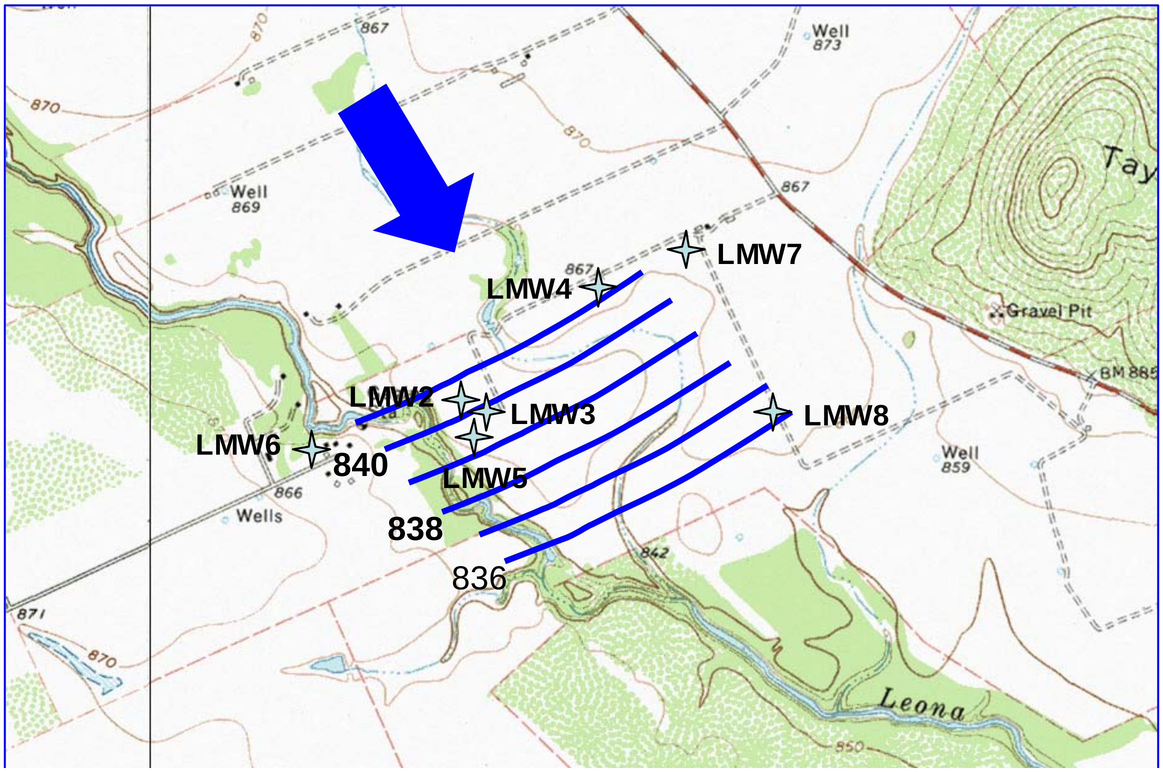

Figure 5. Groundwater flow contours using groundwater elevations recorded at monitoring wells LMW2, LMW3, MW4, LMW5, LMW6, and LMW8 on January 23, 1998. Elevations are in feet above sea level.

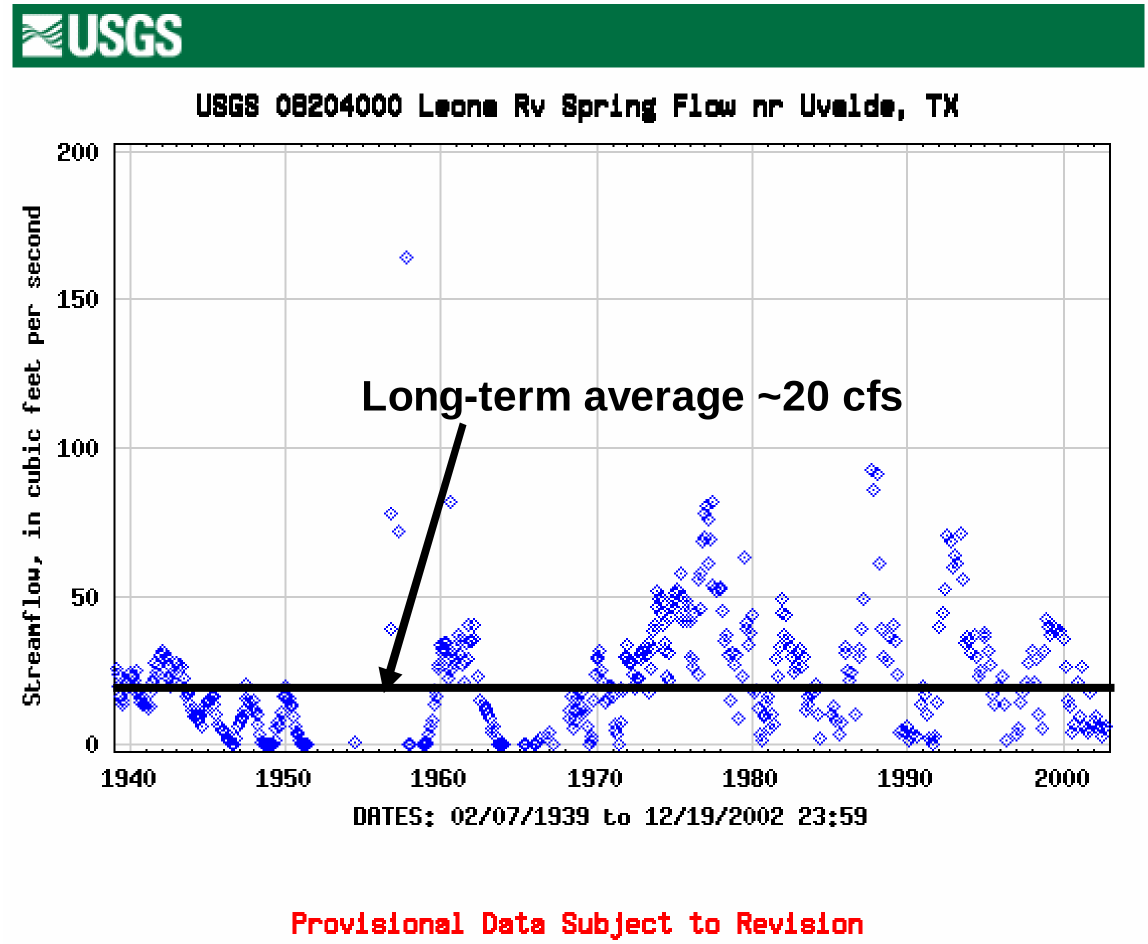

Figure 6. Surface water discharge measured by the USGS at the Leona River gauging station (08204000) for the period 2/7/1039 to 12/19/02. Discharge is presented in cfs.

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