APPLICATION OF MAGNETIC RESONANCE SOUNDINGS FOR HYDROSTRATIGRAPHIC CHARACTERIZATION OF AN ALLUVIAL AQUIFER FOR GROUND-WATER MODEL INPUT

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ABSTRACT

An integrated surface geophysical pilot study at the Texas A&M University Brazos River Hydrologic Field Research Site (BRHFRS), College Station, Texas, was done to determine the effectiveness of methods for defining the hydrostratigraphic framework and hydrogeologic properties for a ground-water availability model. Time-domain electromagnetic (TDEM) soundings and direct-current (2D–DC) resistivity imaging were used to define the lateral and vertical extent of the Brazos River alluvium aquifer, the Ships clay within the aquifer, and the Yegua Formation underlying the aquifer at the BRHFRS. Magnetic resonance soundings (MRS) were used to derive estimates of hydrogeologic properties including percentage water content, transmissivity, and hydraulic conductivity. Stratigraphically, the principal finding of this study was the relation between electrical resistivity and the depth and thickness of the subsurface geologic units at the site. Not only could thicknesses and extents of these units be defined to a greater level than previously interpreted, but lateral variations in resistivity within the alluvium aquifer also could be detected. MRS data have added supporting data to the 2D–DC resistivity and TDEM data allowing for improved understanding of the hydrostratigraphic framework. Hydrostratigraphically, individual hydraulic conductivity values derived from MRS were in close agreement with previously conducted aquifer tests. Average hydraulic conductivity values from the aquifer test are about 61 to 80 m/d, whereas, the MRS-derived hydraulic conductivity values are about 27 to 97 m/d. Results from the geophysics study demonstrated the usefulness of combined TDEM, 2D–DC resistivity, and MRS methods to reduce the need for additional boreholes and to create more accurate ground-water availability models using the acquired data.

INTRODUCTION

The Brazos River alluvium aquifer is used primarily as a source of supply for drinking water and agriculture in Texas and is defined by the Texas Water Development Board (TWDB) as a minor aquifer (Ashworth and Hopkins, 1995). A projected doubling of the Texas population by 2050, as well as the constant threat of drought, necessitates the development of effective water-management plans and requires accurate characterization of both the geology and hydrostratigraphy of the aquifer. A ground-water availability model (GAM) for the Brazos River alluvium aquifer needs valid hydraulic conductivity, transmissivity, storage coefficients, and other properties to simulate changes in water levels in the aquifer due to pumping and drought conditions. The GAM includes information on hydrostratigraphic characteristics such as hydraulic conductivity, specific capacity, and transmissivity (Shah and Houston, 2007); however, numerous data gaps exist throughout the extent of the aquifer and require collection of additional information on the aquifer.

In July 2006, the U.S. Geological Survey (USGS), in cooperation with the TWDB, did an integrated geophysical pilot study at the Texas A&M University Brazos River Hydrologic Field Research Site (BRHFRS) near College Station, Tex. (fig. 1), using two surface geophysical methods—time-domain electromagnetic (TDEM) soundings and two-dimensional direct-current (2D–DC) resistivity imaging to estimate the thickness, extent, and lateral variation in the resistivity of the hydrostratigraphic units—the alluvium of the Brazos River alluvium aquifer, the Ships clay within the aquifer, and the Yegua Formation underlying the aquifer at the BRHFRS. A third method, magnetic resonance sounding (MRS), was used to estimate the hydraulic properties, specifically percentage water content, transmissivity, and hydraulic conductivity at the BRHFRS. These data were integrated to identify the relations between the distribution of resistivity and hydraulic properties in the Brazos River alluvium aquifer and to identify hydrostratigraphic boundaries of the Ships clay, the alluvium of the Brazos River alluvium aquifer, and Yegua Formation.

This paper describes the results from the MRS and other surface geophysical methods and characterizes the hydrostratigraphy of the Brazos River alluvium aquifer. The MRS part of the pilot study was done to compare previously collected hydraulic conductivity data from aquifer tests in the study area with MRS-derived hydraulic conductivity data. The paper also documents an integrated surface geophysical approach in which the hydrostratigraphy of the Brazos River alluvium aquifer at the BRHFRS was interpreted from surface geophysical methods.

HYDROGEOLOGIC SETTING

The BRHFRS encompasses 8.5 square hectometers of the Brazos River floodplain about 15 kilometers (km) southwest of College Station and 200 meters (m) west of the Brazos River (fig. 1). The BRHFRS was initially established in 1993 at the Texas A&M University Research Farm to study ground-water flow and agricultural chemical transport in the Brazos River alluvium aquifer (Munster and others, 1996). Nests of wells at the BRHFRS were installed to monitor water quality and to assess horizontal and vertical ground-water gradients in the Brazos River alluvium aquifer.

From oldest to youngest, the geologic units at the BRHFRS are the Tertiary-age Yegua Formation (fig. 2), a shale that functions as the basal confining unit of the alluvium aquifer at an average depth of about 21 m below land surface. The Yegua Formation is overlain by the Quaternary-age Brazos River alluvium, which is divided into two hydrostratigraphic units—an alluvium aquifer and an upper leaky confining unit (fig. 2). The Brazos River alluvium aquifer is characterized by a fining-upward sequence of coarse sand and gravel at the base to fine sand at the transition zone between the aquifer and the upper leaky confining unit. The upper leaky confining unit (locally named the Ships clay) varies in thickness from about 5 m in the western part of the site to 9 m near the Brazos River (Wrobleski, 1996). The transition from the Ships clay to the Brazos River alluvium aquifer is abrupt with only a 0.3- to 0.6-m transition zone consisting of a sandy clay layer (Munster and others, 1996). The water table in the aquifer generally is immediately below the clay at a depth of about 9 m during the summer.

Nine well nests were drilled at the site to monitor ground-water flow (Munster and others, 1996). A hydrostratigraphic section was constructed on the basis of the driller's logs during the installation of the monitoring wells at the BRHFRS (Munster and others, 1996). Four monitoring wells constitute each well nest; the naming convention for the wells is shown in Figure 3. The well nest identifier (MWA1, 2, or 3; MWB1, 2, or 3 or MWC1, 2, or 3) precedes a well number (1 through 4) for the shallowest to deepest wells. A series of aquifer tests were done at the BRHFRS in 1996 to obtain hydraulic properties of the aquifer (Wrobleski, 1996). The average for each well is based on multiple aquifer tests for each interval. All hydraulic conductivity data from the 1996 aquifer tests were compared to the MRS-derived hydraulic conductivity data.

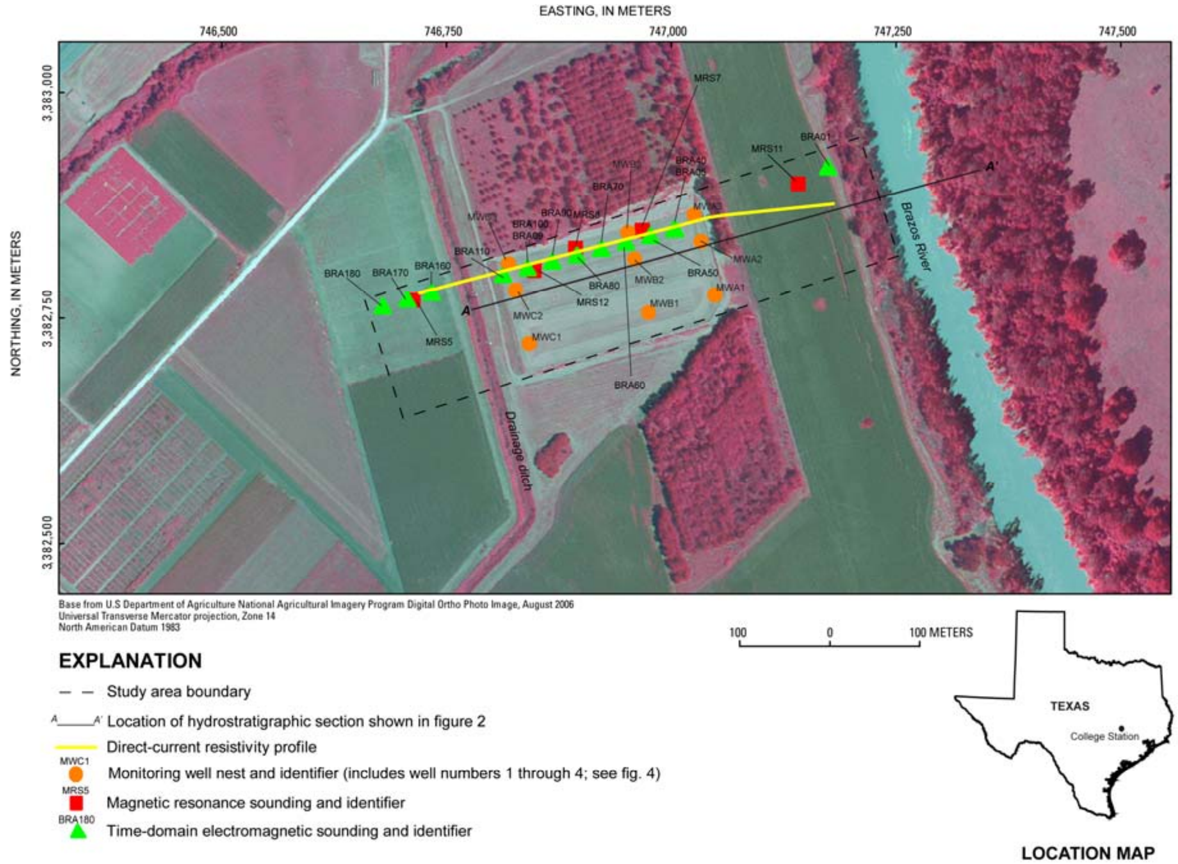

Figure 1: Location of the Texas A&M University Brazos River Hydrologic Field Research Site, College Station, Texas.

Table 1: Summary of average hydraulic conductivity of shallow, intermediate, and deep wells for each well nest at the Brazos River Hydrologic Field Research Site, College Station, Texas.

Well nest	Well identifier (shallow)	Average hydraulic conductivity	Well identifier (intermediate)	Average hydraulic conductivity	Well identifier (deep)	Average hydraulic conductivity	Average hydraulic conduct-ivity for each well nest
A1	MWA1-2	--	MWA1-3	--	MWA1-4	--	--
A2	MWA2-2	63	MWA2-3	57	MWA2-4	55	58
A3	MWA3-2	--	MWA3-3	--	MWA3-4	68	68
B1	MWB1-2	66	MWB1-3	67	MWB1-4	63	65
B2	MWB2-2	64	MWB2-3	65	MWB2-4	62	64
B3	MWB3-2	66	MWB3-3	69	MWB3-4	--	68
C1	MWC1-2	82	MWC1-3	80	MWC1-4	79	80
C2	MWC2-2	77	MWC2-3	--	MWC2-4	93	85
C3	MWC3-2	73	MWC3-3	75	MWC3-4	75	74

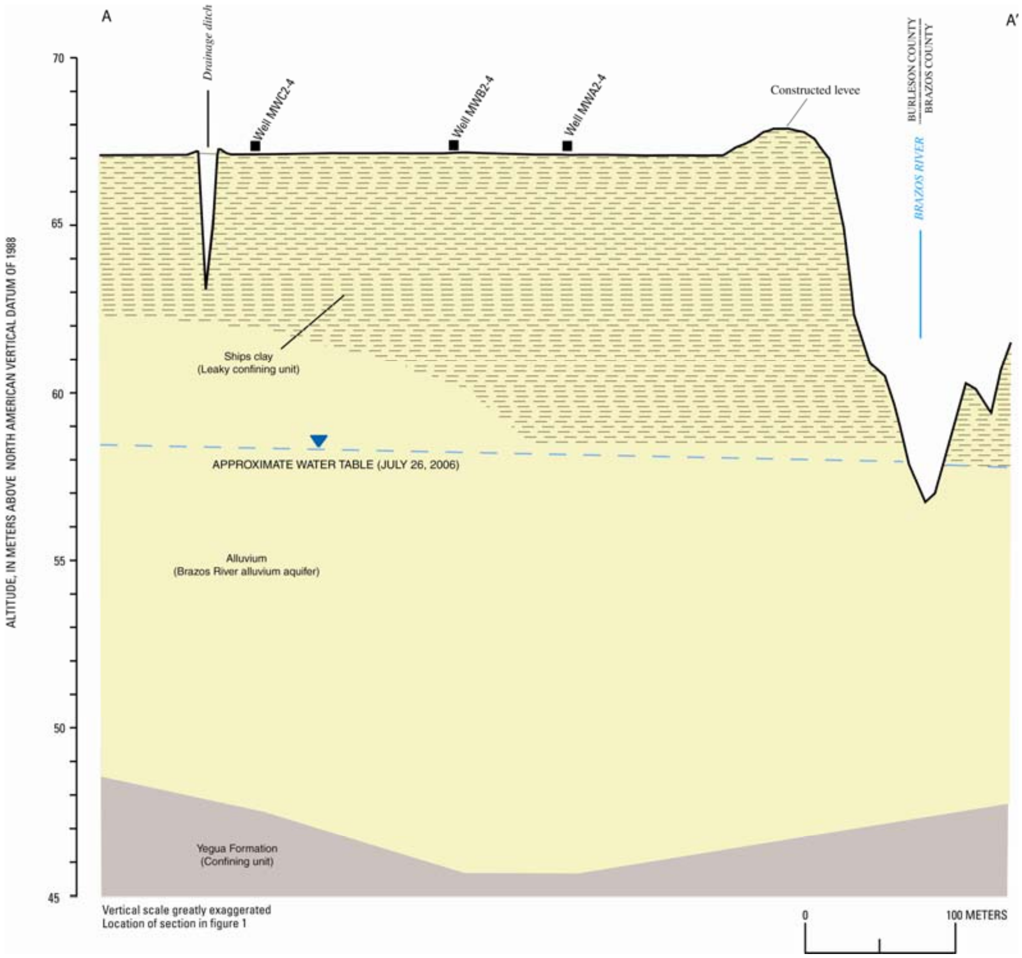

Figure 2: Conceptual hydrostratigraphic section A-A' across the Brazos River Hydrologic Field Research Site, College Station, Texas (modified from Wrobleski, 1996).

GEOPHYSICAL METHODS

TDEM and 2D–DC resistivity were used to characterize the electrical stratigraphy of the BRHFRS. These methods were used to measure the thickness, extent, and lateral variation in the resistivity of the subsurface, which could then be used to define the correlation between electrical stratigraphic units and hydrostratigraphic units. MRS was used to estimate the hydraulic properties, specifically percentage water content, transmissivity, and hydraulic conductivity at the BRHFRS. These data were integrated to identify the relations between the distribution of resistivity and hydraulic properties in the Brazos River alluvium aquifer and to identify hydrostratigraphic boundaries. The survey was designed so that multiple methods could be used to achieve a more comprehensive analysis of the subsurface at BRHFRS.

Time-Domain Electromagnetic Soundings

Fourteen TDEM sounding sites were selected to provide a uniform distribution of data to define the framework of the electrical stratigraphy across the BRHFRS (fig. 1). The Geonics Protem-47 and -57 systems used nine 20-square-meter (m^2) and five 40-m^2 transmitter loops to collect the TDEM soundings (Geonics Ltd., 2005).

For each sounding, the voltage data were averaged and evaluated statistically. The raw field data (voltage data) first were checked for uncertainty by computing the standard deviation of the voltage data from each duty cycle. The raw voltage data were then averaged over each duty cycle for each gate for each frequency using TEM2IX1D (Interpex Ltd., 2006). The data were then imported into the inverse modeling software IX1D version

3 (Interpex Ltd., 2006). Voltages with standard deviation greater than 5 percent were deleted before modeling, which eliminated data from late-time gates that yielded the highest signal-to-noise ratios. Data that deviated severely from the curve were deleted before inverse modeling. A smooth model consisting of 25 layers with a minimum depth of 1 m, a maximum depth of 60 to 75 m, and a starting resistivity of 10 ohm-meters (ohm-m) were used to approximate the measured resistivity points in the starting model. A simple layered-earth model was constructed by comparing inflections observed in the smooth model results to the number of hydrostratigraphic units observed in the driller's log data from the BRHFRS monitoring wells.

Final root-mean square (RMS) errors from smooth model and layered-earth model inversion results ranged from 1.15 to 6.31 percent and from 1.09 to 6.27 percent, respectively. Any sounding with an RMS error greater than 5 percent was given less weight than the others because of the uncertainty in the data. Inversion results depicted a distinct electrical contrast between the Ships clay (clay), the alluvium of the Brazos River alluvium aquifer (sand and gravel), and the Yegua Formation (shale).

Two-Dimensional Direct-Current Resistivity

The 2D–DC resistivity survey was done using the IRIS Instruments Syscal Pro system (Iris Instruments, 2006) that incorporates 96 electrodes spaced 5 m apart. A 480-m 2D–DC resistivity profile was collected to measure the subsurface distribution of electrical properties using the dipole-dipole array. The raw field data (current and voltage data) first were checked for uncertainty by evaluating the standard deviation of the computed apparent resistivity data using Prosys II version 2.10.02 (Iris Instruments, 2006). Apparent resistivity data with standard deviation less than 0 were removed, resulting in the removal of 92 data points related to low signal-to-noise values. After filtering, 10 additional data points (three on data level 1 and seven on data level 9.1) were removed because of a lack of data per data level (Loke, 2000). The data were then filtered by applying a moving average to all depth levels with a span of 10 m. The final apparent resistivity dataset was imported into the 2D inverse modeling software RES2DINV version 3.55 (Loke, 2004). Apparent resistivity data were inverted using the blocky inverse modeling technique by selecting the robust constraint option in RES2DINV. After inversion the RMS error between the measured and calculated apparent resistivity data was 2.2 percent. Generally RMS errors less than 5-10 percent can be expected.

Magnetic Resonance Soundings

Because this was a pilot study, the MRS modeling and interpretations are preliminary. Numis^{PLUS} magnetic resonance equipment (Iris Instruments, 2006) was used to collect five soundings along a single profile across the study area (fig. 1). The square-eight antenna was used to improve the signal-to-noise ratio thus minimizing the effects of nearby power lines that run parallel to the profile where four of the soundings were collected (Legchenko and others, 2004). Because of a lack of space and increased signal-to-noise values, sounding MRS5 used a 50-m^2 square antenna to alleviate some of the high-noise measurements. The Larmor frequency was calculated by the system on the basis of the Earth's magnetic field in the study area and was set to 2,076.9 hertz (Hz) throughout the BRHFRS. The duration of current of the pulse was set to 40 milliseconds (ms). The recording time of the receiver was set to 240 ms to ensure that the voltage decay would be recorded until the voltage decreased below the background noise level of the area. Using these parameters, high-quality MRS data were acquired owing to a favorable signal-to-noise ratio indicated by the low mean noise relative to the signal amplitude (fig. 3).

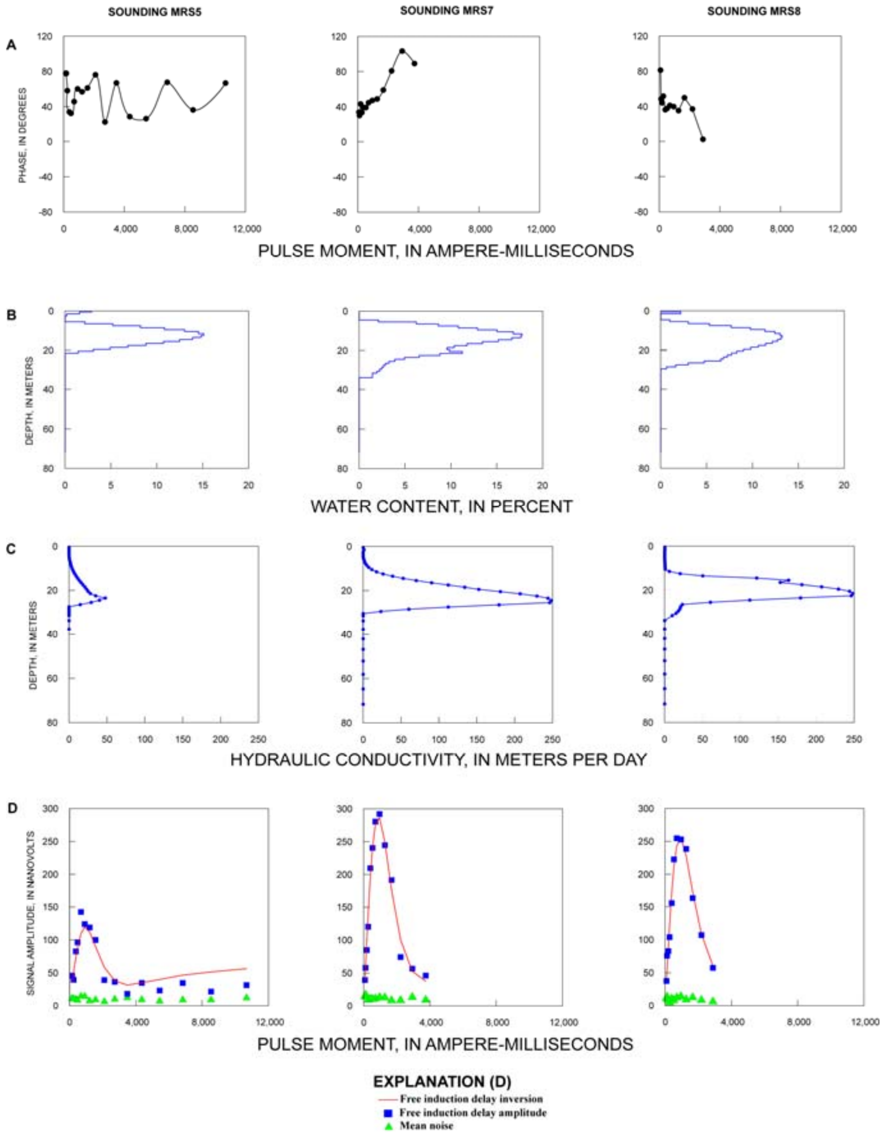

Figure 3: Magnetic resonance sounding (MRS) inversion results: (A) phase relative to pulse moment, (B) depth relative to water content, (C) depth relative to hydraulic conductivity, and (D) pulse moment relative to signal amplitude with signal-to-noise indication.

Prior to MRS data inversion, a matrix for each sounding site was created. The matrix was constrained by the following model parameters: antenna type, magnetic field inclination of the study area, maximum depth of the matrix, resistivity of layered-earth models obtained from the TDEM data, and the calculated maximum pulse moment (table 2). The magnetic field inclination, used in the relaxation time calculation, was calculated using the geospatial coordinates of each sounding and was about 60 degrees for the entire study area. The maximum depth of the matrix was set at 75 m as limited by the size of the antenna loop used.

Table 2: Matrix parameters used in magnetic resonance sounding inversion, Brazos River Hydrologic Field Research Site, College Station, Texas.

Sounding (fig. 1)	Antenna type	Antenna side length (meters)	Resistivity layer	Depth to bottom of layer (meters below land surface)	Resistivity (ohm-meters)	Calculated pulse moment maximum (ampere-milliseconds)
MRS5	Square	50	1	2.80	4.50	10,682.80
			2	16.70	35.30	
			3	29.50	10.10	
			4	75.00	4.20	
MRS7	Square eight	50	1	4.30	4.10	7,323.20
			2	18.10	29.40	
			3	38.10	9.60	
			4	75.00	3.00	
MRS8	Square eight	50	1	2.70	3.20	7,296.00
			2	17.60	37.60	
			3	38.20	7.50	
			4	75.00	3.00	
MRS11	Square eight	50	1	2.80	26.70	7,000.00
			2	10.10	5.10	
			3	22.70	24.30	
			4	44.50	6.90	
			5	75.00	2.70	
MRS12	Square eight	50	1	3.30	4.80	7,000.00
			2	16.40	31.80	
			3	31.60	9.00	
			4	75.00	4.20	

Samovar, a program developed by Iris Instruments (2006), was used for the MRS data inversion process. Standard default parameters first were used to derive hydraulic conductivity values. However, exclusively using these default parameters during inversion resulted in hydraulic conductivity values that were substantially greater (5 to 10 times) than those computed from aquifer tests. Consequently, an alternate inversion method described by Legchenko and others (2004) was used.

The constraints necessary for inversion include processing time, regularization parameters E (observed relaxation time) and T1* (longitudinal relaxation time), and the coefficient of permeability (*Cp*). Default parameters maintained by the Samovar program for inversion include the processing time (198.4 ms), which corresponds to the Numis^{PLUS} measurement-time window (Iris Instruments, 2006) and bandpass filter (10 Hz), The inversion program provides the best solution for T1* on the basis of the total response of the magnetic resonance signal.

If necessary after inversion, T1* can be optimized to make the inversion solution for each sounding more definitive in terms of changes with depth in hydraulic conductivity, transmissivity, or signal-to-noise ratio (Legchenko and others, 2004). Using the default *Cp* value of 7.00×10^{-9} assigned by the Samovar program, T1* is calibrated by running a series of inversions with different values of T1* (13 in this application) in the range of 1 to 1,000. Using transmissivity as an example, the resulting transmissivity values and fitting error for each inversion were then normalized (divided by the respective maximum). The normalized values were summed for each inversion and graphed relative to T1* (fig. 4).

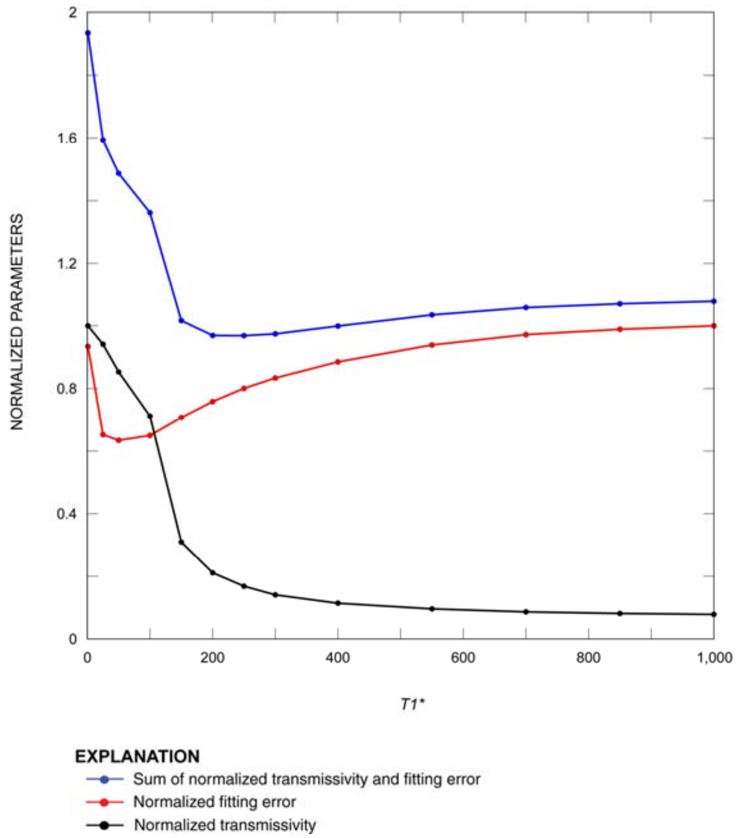

Figure 4: Calibration graph used to obtain the optimum relaxation time (T1*) for inversion of magnetic resonance sounding data using the default coefficient of permeability (*Cp*) value of 7.00 x 10^{-9} ,Brazos River Hydrologic Field Research Site, College Station, Texas.

The graph (and a similar one for each sounding) shows a curve with a flat segment corresponding to essentially equivalent solutions. The optimal solution is chosen to be the center of the flat segment and defined as a regularized solution that yields a value of T1* with a reasonable fitting error. The maximum, minimum, and optimum transmissivity values for each MRS sounding are listed in table 3. The saturated thickness is then determined for each sounding and divided by the optimum transmissivity to yield an MRS-derived hydraulic conductivity (table 3).

Table 3: Minimum, maximum, and optimal transmissivity, saturated thickness, and magnetic resonance sounding (MRS)-derived hydraulic conductivity values obtained from default coefficient of permeability (*Cp*) value (7.00 x10^{-9}), Brazos River Hydrologic Field Research Site, College Station, Texas.

Sounding (fig. 1)	Minimum transmissivity (meters squared per day)	Maximum transmissivity (meters squared per day)	Optimum transmissivity (meters squared per day)	Saturated thickness (meters)	MRS-derived hydraulic conductivity (meters per day)
MRS5	147	181	164	15	11
MRS7	225	294	242	14	17
MRS8	302	510	415	16	26
MRS11	104	156	121	17	7
MRS12	294	389	328	15	22

To more accurately represent the hydraulic conductivity of the soundings collected in the Brazos River alluvium aquifer in the study area, a *Cp* value that is more representative of the study area was manually calibrated. Data from two soundings and four monitoring well nests were used to calibrate *Cp* and then to calculate hydraulic conductivity. Well nests MWB3 and MWB2 (fig. 1) correspond to MRS sounding 7 data and well nests MWC3 and MWC2 correspond to MRS sounding 12 data. Only MRS soundings 7 and 12 were used to calibrate *Cp* because of their proximity to monitoring well nests in the study area with previously obtained hydraulic conductivity values that can be compared directly with MRS-derived hydraulic conductivity values. First, the hydraulic conductivity values obtained from the 1996 aquifer tests (Wrobleski, 1996) for well nests MWB3 and MWB2 were combined and averaged, and then those for well nests MWC3 and MWC2 were combined and averaged to obtain two hydraulic conductivity values (table 4).

Table 4: Sounding, corresponding monitoring well nest, average hydraulic conductivity from 1996 aquifer tests, and average monitoring well nest hydraulic conductivity used to calibrate coefficient of permeability (*Cp*), Brazos River Hydrologic Field Research Site, College Station, Texas.

Sounding	**Well nest**	**Average hydraulic conductivity from 1996 aquifer test (meters per day)**	**Well nest**	**Average hydraulic conductivity from 1996 aquifer tests (meters per day)**	**Average monitoring well nest hydraulic conductivity (meters per day)**
MRS7	MWB3	68	MWB2	64	66
MRS12	MWC2	85	MWC3	74	80

Two correction factors (table 5) are then computed by dividing the average monitoring well hydraulic conductivity corresponding to MRS soundings 7 and 12 (table 4) by the MRS-derived hydraulic conductivity obtained by using the default *Cp* value (table 3) for both soundings. The average of these correction factors then is multiplied by the default *Cp* value (7.00×10^{-9}) to obtain a corrected *Cp* value of 2.61×10^{-8} (table 5). The corrected *Cp* value is then used in the inversion.

After the inversion process, a series of calculated data outputs—raw decay curves, water content, hydraulic conductivity, and signal amplitude—were generated (fig. 3). The results from MRS inverse modeling (fig. 4) can assist in estimating the percentage water content and hydraulic conductivity of the hydrostratigraphic units. Specifically, the output data for each sounding generated from the MRS inversion include phase relative to pulse moment (fig. 3A); depth relative to water content (fig. 3B); depth relative to hydraulic conductivity (fig. 3C); and raw voltage decays for each signal amplitude observed in the field and best-fit line to each decay (shown in red) (fig. 3D). A final hydraulic conductivity value for each sounding based on the MRS results was derived and compared with the previously calculated values from the 1996 aquifer tests (table 6).

Table 5: Corrected coefficient of permeability (*Cp*) value computed using magnetic resonance sounding (MRS)-derived hydraulic conductivity from default *Cp* value (7.00×10^{-9}), average monitoring well nest hydraulic conductivity, and correction factor, Brazos River Hydrologic Field Research Site, College Station, Texas. [[a] Well nests MWB3 and MWB2; [b] Well nests MWC2 and MWC3]

Sounding	**MRS-derived hydraulic conductivity (m/d)**	**Average monitoring well nest hydraulic conductivity (m/d)**	**Correction factor**	**Average correction factor**	**Corrected *Cp***
MRS7	17	66[a]	3.82	3.73	2.61×10^{-8}
MRS12	22	80[b]	3.63		

Table 6: Minimum, maximum, and optimum transmissivity and magnetic resonance sounding (MRS)-derived hydraulic conductivity values obtained from the corrected coefficient of permeability (*Cp)* value (2.61 x10^{-8}) compared with average hydraulic conductivity values from closest monitoring well nest calculated from 1996 aquifer tests, Brazos River Hydrologic Field Research Site, College Station, Texas. [[a] Average for well nests MWC2 and MWC3; about 110 meters from MRS5; [b] Average for well nests MWB3 and MWB2; about 20 meters from MRS7; [c] Average for well nests MWB2, MWB3, MWC2, and MWC3; about 60 meters from MRS8; [d] Average for well nests MWA2 and MWA3; about 120 meters from MRS11; [e] Average for well nests MWC2 and MWC3; about 30 meters from MRS12]

Sounding	Minimum transmissivity (m^2/d)	Maximum transmissivity (m^2/d)	Optimum transmissivity (m^2/d)	Saturated thickness (m)	MRS-derived hydraulic conductivity (m/d)	Average hydraulic conductivity from closest monitoring well nests (m/d)
MRS5	548	677	612	15	40	80[a]
MRS7	838	1,096	902	14	64	66[b]
MRS8	1,128	1,901	1,547	16	97	73[c]
MRS11	387	580	451	17	27	61[d]
MRS12	1,096	1,450	1,225	15	82	80[e]

CONCLUSIONS

Prior knowledge of the general hydrostratigraphy of the alluvium of the Brazos River alluvium aquifer, the Ships clay, and Yegua Formation is required for comparison with the acquired geophysical data. An integrated interpretation can be made from the TDEM, 2D–DC resistivity, and MRS inversion results. Creating the electrical stratigraphy of the geology from TDEM and 2D–DC resistivity data and the hydrostratigraphy using MRS data enhances the understanding of the hydrostratigraphy of the Brazos River alluvium aquifer. And MRS-derived hydraulic conductivity values can be input to ground-water availability models.

Electrical Stratigraphy and Hydrostratigraphic Framework

Stratigraphically, the principal finding of this study is the relation between electrical resistivity and the depth and thickness of the subsurface hydrostratigraphic units at BRHFRS. Not only could thicknesses and extents of these units be defined to a greater level than previously interpreted, but lateral variations in resistivity within the Brazos River alluvium aquifer also could be detected. The MRS soundings have added supporting data to the 2D–DC and TDEM resistivity profiles allowing for improved understanding of the hydrostratigraphic framework and the related depositional environments.

The TDEM shows a three-layer model in which there is a conductor-resistor-conductor pattern. This correlates with the hydrostratigraphic units within the study area: Ships clay (conductor), alluvium of the Brazos River alluvium aquifer (resistor), and Yegua Formation (conductor). Sharp electrical boundaries that range from 4 to 6 m and 20 to 22 m below land surface, based on the TDEM data, define the more resistive alluvium of the aquifer. The thickest part of the more resistive alluvium of the aquifer is in the middle of the study area between TDEM soundings BRA110 and BRA90 where the thickness is about 17 m (fig. 5C). This is interpreted to be an ancestral channel deposit of the Brazos River that has not been identified previously. This interpretation is based on correlating lithology to resistivity and comparisons of lithology to the 2D–DC and MRS soundings. The higher resistivities indicate coarse sediments (sand and gravel) shown in the driller's logs of figures 5B and 6B.

The 2D–DC resistivity profile provides a good resolution for determining lateral variation of resistivity. According to the 2D–DC resistivity profile, variations in the Brazos River alluvium aquifer range from 10 to more than 175 ohm-m (fig. 5D). These variations are possibly caused by lateral changes in grain size and help define the geometry of the subsurface hydrostratigraphic units (Kress and others, 2006). Resistivity increases from east to west along the profile (fig. 5D) away from the Brazos River toward the interpreted ancestral Brazos River channel. Typically, an increase in resistivity signifies an increase in grain size in the alluvium aquifer, and therefore a more productive aquifer (more water). The highest resistivities, from about 100 to 175 ohm-m, occur over a distance of 200 m. This zone of high resistivity (shown in blue in figure 5D) occurs between TDEM soundings BRA110 and BRA90 and is the thickest section of coarse sediment in the ancestral channel. The zones of lowest resistivity (or high conductivity) occur at the top of the 2D–DC resistivity profile from land surface to about 7 m below land surface and at the base of the profile. These upper and lower zones of low resistivity correlate with the Ships clay and Yegua Formation, respectively. By combining TDEM and 2D–DC resistivity data, information on the aquifer geometry and lateral variations in resistivity were obtained. These data helped build the hydrostratigraphic framework into which the MRS data were integrated. Using this joint interpretation of the resistivity and MRS also helped improved the accuracy of the derived hydraulic conductivity values.

Hydrostratigraphy

MRS data can help delineate the subsurface hydrostratigraphy and identify the geometric boundaries of the hydrostratigraphic units by indicating changes in the free water content, transmissivity, saturated thickness, and hydraulic conductivity (Lubczynski and Roy, 2004). Typically, this is only possible if there is a high signal-to-noise ratio (fig. 3D). If the signal-to-noise ratio is too low, it might not be possible to distinguish hydrostratigraphic boundaries at depth (Lubczynski and Roy, 2004). The aquifer geometry in this application encompasses the lateral extent of porous and permeable materials. On the basis of the gridded MRS-derived water content and hydraulic conductivity data, most of the soundings show that the most productive parts of the Brazos River alluvium aquifer occur from about 15 to 20 m below land surface (fig. 6) in the western part of the study area and become slightly more productive in the eastern part of the area (toward the Brazos River). The profile indicates that the hydraulic conductivity in this productive zone is between 90 and 250 meters per day (m/d) (fig. 6D). Zones of high water content and high hydraulic conductivity occur mostly between and adjacent to MRS soundings 12 and 7 with the highest percentage water content occurring around MRS sounding 7.

The higher values of water content and hydraulic conductivity are consistent with the geology based on the TDEM and 2D–DC resistivity data in which the thickest part of the Brazos River alluvium aquifer is in the middle of the study area. The 2D–DC resistivity data (fig. 5) show a gradual change in resistivity toward the west where the high resistivities indicate an increase in grain size and, therefore, a higher percentage water content and pore space. As the water content and hydraulic conductivity increase farther below land surface, coarser material such as sand and gravel (Brazos River alluvium aquifer) increases.

The TDEM layered models (fig. 5) and the MRS gridded water content profile (fig. 6) verify the aquifer geometry. The abrupt changes in resistivity shown in the TDEM soundings correlate with the depth and thickness of the areas of high and low percentages of water content, particularly in the alluvium of the Brazos River alluvium aquifer. At most of the MRS soundings, the static water level (measured on the same day that the MRS soundings were made) is about 10 m below land surface and therefore very little to no water (shown in yellow in figure 6C) was detected above that depth by the MRS. The minimal water detection above this depth correlates with the compact, clay-rich material (Ships clay) above the water table. At the base of both profiles (figs. 6C and 5D), percentage water content and hydraulic conductivity decrease where the Yegua Formation occurs. Very little or no pore space exists in that unit to hold or transmit water.

Individual hydraulic conductivity values derived from MRS were consistent with those from the 1996 aquifer tests. Average hydraulic conductivity values from the aquifer tests for the closest monitoring-well nests are about 61 to 80 m/d (Wrobleski, 1996), whereas, the MRS-derived hydraulic conductivity values are about 27 to 97 m/d (table 6). The highest hydraulic conductivity values indicated by the gridded hydraulic conductivity profile are between MRS soundings 12 and 7 (fig. 6D). The alluvium aquifer is very heterogeneous in the areas of MRS soundings 5 and 11 based on MRS-derived hydraulic conductivity values that differ greatly from the surrounding hydraulic conductivity values. MRS soundings 5 and 11 also show the greatest discrepancy between the MRS-derived hydraulic conductivity and the average hydraulic conductivity computed from the 1996 aquifer tests (table 6), but these soundings are farthest from the well nests. Interpreting both the gridded profiles and individual hydraulic conductivity values derived from MRS can help generate a conceptualization of the hydrostratigraphy and constrain ground-water models for better accuracy. Collecting supporting data might be necessary to further define the hydrostratigraphy of the Brazos River alluvium aquifer at BRHFRS.

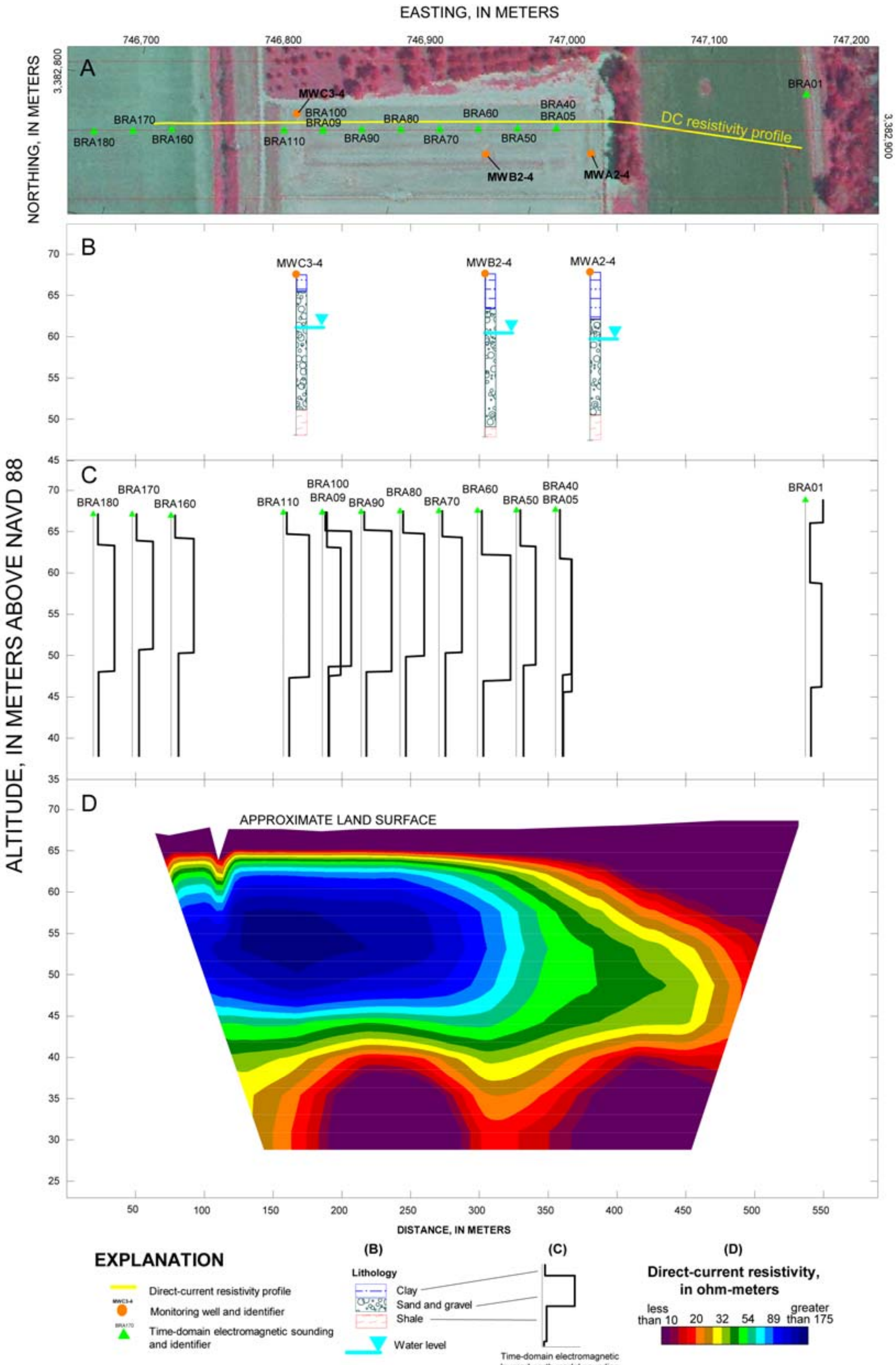

Figure 5: (A) Location of selected wells and time-domain electromagnetic (TDEM) soundings, (B) drillers' logs with static water level, (C) TDEM layered-earth model sounding results, and (D) robust inversion profile of two-dimensional direct-current dipole-dipole resistivity array, Brazos River Hydrologic Field Research Site, College Station, Texas.

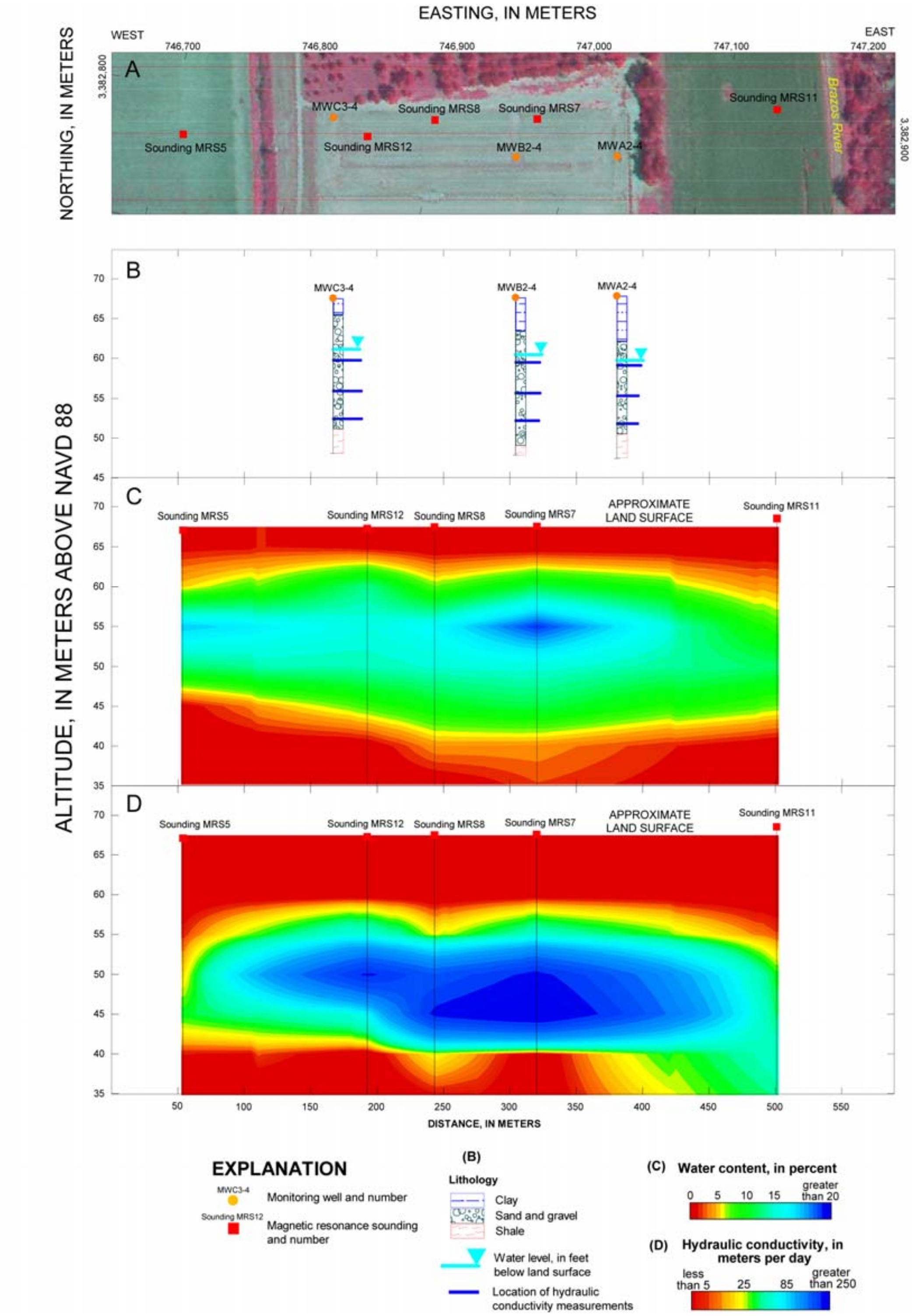

Figure 6: (A) Location of selected wells and magnetic resonance soundings (MRS), (B) drillers' logs with static water-level and locations of hydraulic conductivity measurements, (C) gridded percentage water content profile, and (D) gridded hydraulic conductivity profile based on MRS results, Brazos River Hydrologic Field Research Site, College Station, Texas.

Hydrostratigraphic Unit Parameterization

Aquifer and confining-unit properties for ground-water modeling usually are obtained from aquifer tests or calculated from known variables. However, MRS also can be used to obtain hydrostratigraphic data for input into ground-water models. Because of the large volume of material MRS is able to measure, properties such as transmissivity, water content, and hydraulic conductivity can be estimated over a larger area and depth, whereas aquifer tests yield data from a discreet point in the aquifer. The MRS soundings allow for many more data points to supplement aquifer-test sites, thus providing more comprehensive coverage of aquifer properties. In this Brazos River alluvium aquifer study, MRS helps define the hydrostratigraphic units and vertical aquifer boundaries essential for input into ground-water models (Plata and Rubio, 2006).

On the basis of historical literature, Brazos River Basin regional hydraulic conductivity ranges from about 2 m/d north of the study area to about 130 m/d south of the study area (Shah and Houston, 2007). The MRS data collected at the site are well within this range and confirm that the MRS method is capable of obtaining hydrostratigraphic unit properties at the BRHFRS. On the basis of data collected at the site, MRS could be used in areas in the Brazos River alluvium aquifer where data are lacking and can be used in conjunction with ground-water availability modeling. In comparison to small-scale hydrologic property measurements and expensive aquifer tests, MRS has been shown to be an effective method to investigate large volumes of the subsurface (based on the size of the loop). For ground-water models, MRS can provide a comprehensive distribution of properties for model cells (Roy and Lubczynski, 2003).

Disclaimer

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