Characterizing oil field salinization using airborne, surface, and borehole geophysics: An example from the Upper Colorado River Basin, Texas

Jeffrey G. Paine and Edward W. Collins

ABSTRACT

Multidisciplinary investigations of natural and oil field salinization along the upper Colorado River, Texas, present an opportunity to integrate results from a stream-axis airborne geophysical survey, ground and borehole geophysical surveys, and well drilling and sampling. Airborne electromagnetic (EM) induction measurements along 437 km (272 mi) of river and tributary stream axes identified discrete salinized streambed segments, including several near oil fields. Identification of these salinized streambed segments allowed more intensive and invasive investigations to be focused on the most significant near-river sources of salinity. One of these streambed segments lies adjacent to an oil field, where production began in the 1950s before discharge of coproduced brine into surface pits was prohibited in Texas. Monitor wells drilled after the airborne survey verified groundwater salinization in the oil field but did not adequately delineate salinization nor identify specific salinity source areas. Subsequent ground and borehole geophysical surveys complemented airborne EM induction and well data by establishing lateral and vertical salinization bounds in the oil field, discovering possible salinity source areas, and determining optimal locations for additional wells.

INTRODUCTION

Multidisciplinary environmental investigations in an oil field adjacent to the upper Colorado River in west Texas illustrate how phased minimally invasive airborne, surface, and borehole geophysical

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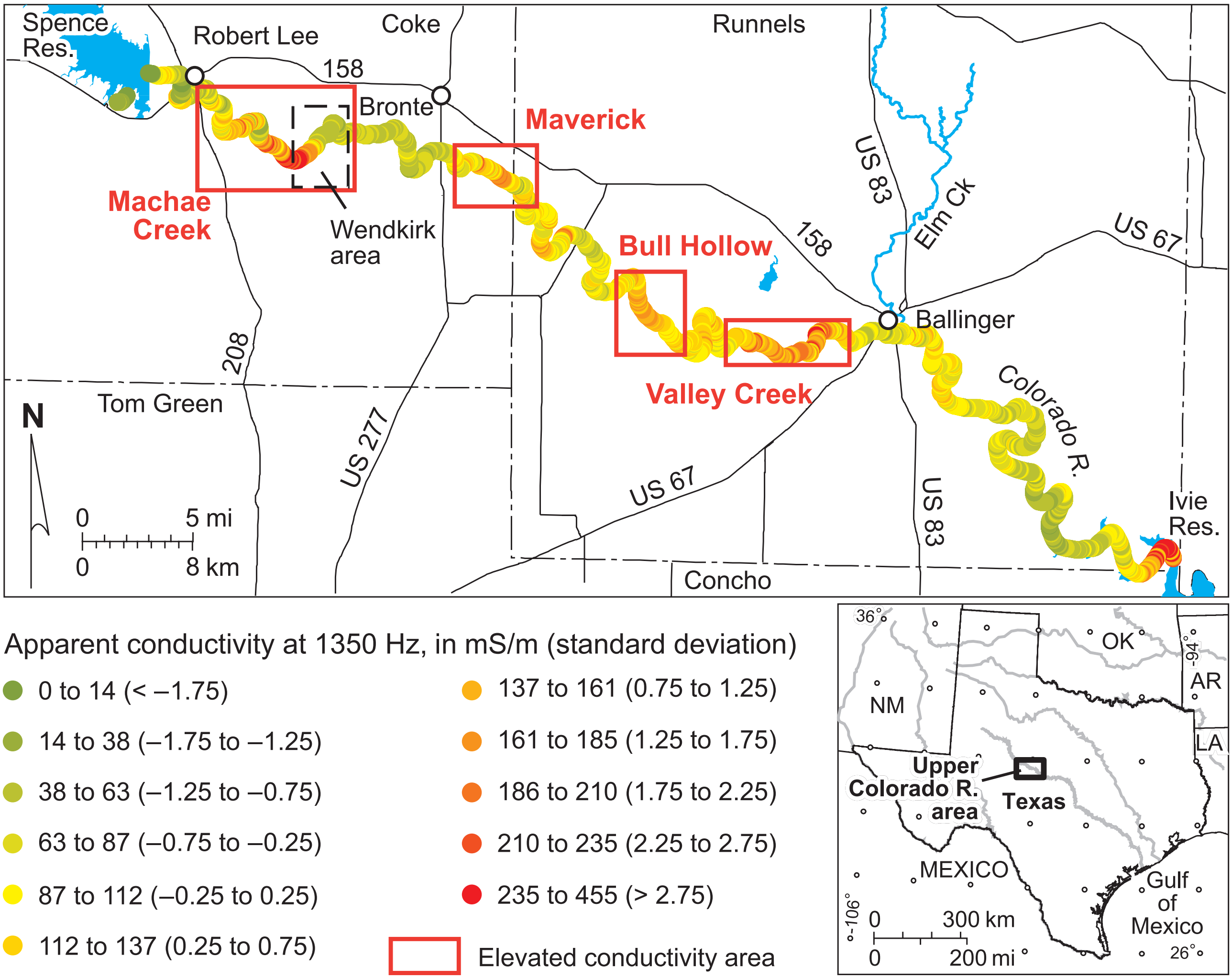


Figure 1. Apparent conductivity measured at 1350 Hz along the axis of the Colorado River during the 2005 airborne geophysical survey (Paine et al., 2006, 2009). Elevated conductivity segments indicating locations of possible saline-water inflow are bounded by red rectangles. The dashed box within the Machae Creek area encloses the Wendkirk oil field area shown in Figure 3.

methods can be integrated to characterize salinization that degrades surface and groundwater quality in many older fields, where brines have been introduced into the near-surface environment. We conducted surface and borehole geophysical surveys in and near Wendkirk oil field in Coke County, Texas (Figure 1), to investigate the lateral and vertical extents of salinization impacting water quality in the upper Colorado River. These focused studies follow those reported in Paine et al. (2006, 2009), in which a multifrequency electromagnetic (EM) induction instrument was flown along the axis of the upper Colorado River and a major tributary to identify areas where high streambed electrical conductivities suggest sites of saline-water inflow into the river. The Machae Creek area, which encompasses Wendkirk oil field, was the farthest upstream of four elevated conductivity zones identified between two Colorado River reservoirs (Spence and Ivie) as revealed by the airborne survey (Figure 1). The ground and borehole geophysical investigations in the Wendkirk area were intended to clarify the extent of natural and oil field salinization, select optimal locations for monitor wells, and guide remedial efforts.

Wendkirk oil field was discovered in the 1950s and produces from the Pennsylvanian Cisco Group (Wilson, 1973; Handbook of Texas Online, 2010). It serves as a representative older west Texas oil field that was active when surface discharge of coproduced brine was allowed in Texas. Before the Railroad Commission of Texas amended its water protection Rule 8 in 1969 to include a “no-pit” order, produced water was permitted to be discharged into surface pits. The existence of former brine disposal pits in Wendkirk oil field is evident from historical aerial photographs and field investigations. State records show that as late as 1961, total annual brine production in Wendkirk oil field was about 270,000 bbl, of which at least 15,000 bbl was discharged into surface pits (Wilson, 1973) and the remainder injected into the subsurface. Greater volumes were discharged into pits before 1961. Countywide data for 1957 show that 24% (654,000 bbl) of produced water was disposed at the surface (Slade and Buszka, 1994).

Electrical geophysical methods, including EM induction and resistivity, are well suited to salinization investigations, whether conducted from the air, on water, on the ground, or in boreholes. Electrical methods are popular because they can be rapidly and noninvasively applied. They are effective because a large increase in electrical conductivity typically accompanies the introduction of extremely conductive saline water (several hundred to several thousand milliSiemens per meter [mS/m]; Hem, 1985) into fresh water, soil, and rock that generally have low natural conductivities (a few to a few hundred mS/m; McNeill, 1980a; Palacky, 1987). Common strata in this part of the upper Colorado River basin include Paleozoic shale, sandstone, conglomerate, and gypsum and Quaternary alluvium (Beede and Bentley, 1918). These strata have logged bulk conductivities in nonsalinized areas that range from a few tens to 100 mS/m or more, reflecting variations in mineral grain conductivity, water saturation, and ionic concentration of pore fluid. In contrast, produced water from upper Colorado River basin oil fields has reported chloride concentrations as great as 80,860 mg/L and electrical conductivities greater than 10,000 mS/m (Slade and Buszka, 1994; Paine et al., 2009). When produced water of these extreme conductivities infiltrates media with typical porosities of 25% or more, bulk whole-rock conductivities increase significantly through increased electrolytic conduction and are readily detectable using airborne, surface, and borehole electrical geophysical methods.

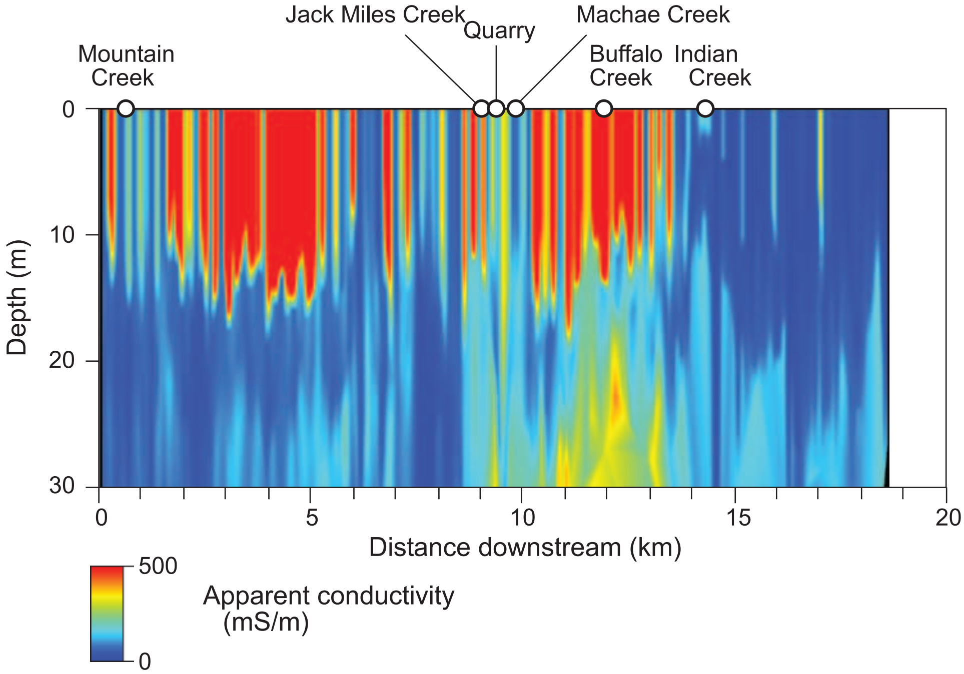
METHODS

We used airborne, surface, and borehole EM instruments to measure the electrical conductivity of the ground to delineate salinization in the study area. Airborne data were used to identify specific stream segments such as the Machae Creek area where saline water could be flowing into the Colorado River (Paine et al., 2009). Measurements using ground-based instruments along transects at and near the river and local drainages were used to delineate near-surface salinization across the oil field. Borehole conductivity logs revealed detailed vertical conductivity profiles that helped identify specific subsurface strata units carrying highly saline water. Ground-based EM soundings served as borehole proxies to determine generalized vertical conductivity profiles that also detected salinized subsurface strata to depths of 50 to 100 m (164–328 ft).

We used frequency-domain EM (FDEM) and time-domain EM (TDEM) methods to measure apparent electrical conductivity. Frequency-domain EM methods use a changing primary magnetic field created around a transmitter coil to induce current to flow in the ground, which in turn creates a secondary magnetic field that is sensed by the receiver coil (Parasnis, 1986; Frischknecht et al., 1991; West and Macnae, 1991). The strength of the secondary field is a complex function of EM frequency and ground conductivity (McNeill, 1980b) but generally increases with ground conductivity at constant frequency. Time-domain EM devices measure the decay of a transient secondary magnetic field produced by currents induced to flow in the ground by the termination of a primary electric current (Kaufman and Keller, 1983; Spies and Frischknecht, 1991) flowing in a transmitter loop. The strength of the decaying secondary field (the transient) is measured by the receiving coil at discrete time intervals after transmitter current termination. In horizontally layered media, secondary field strength at early times gives information on conductivity in the shallow subsurface. Field strength at later times is influenced by conductivity at depth. Computer programs are used to invert the characteristic shape and strength of the decaying transient into multilayer models of conductivity variation with depth. Exploration depths can range from several meters to hundreds of meters depending on instrument configuration, ground characteristics, and electromagnetic noise.

The EM methods have proven to be effective in locating salinized areas, mapping the extent and intensity of salinization, and locating potential salinity sources. Early instruments used to estimate soil salinity indirectly included in situ transducers and electrode arrays to measure soil conductivity (Enfield and Evans, 1969; Halvorson and Rhoades, 1974). During the late 1970s and early 1980s, investigators began developing and using EM instruments to measure ground conductivity noninvasively and estimate soil and water salinity (De Jong et al., 1979; McNeill, 1980a, b; Rhoades and Corwin, 1981; Corwin and Rhoades, 1982, 1984; Williams and

Figure 2. Combined apparent conductivity pseudodepth section along the Machae Creek segment of the Colorado River (Figure 1) from all frequencies acquired during the airborne geophysical survey. Apparent conductivities are combined with calculated centroid depths for each frequency to produce the sections. Wendkirk oil field lies adjacent to the deep elevated conductivity zone that begins at a downstream distance of about 11 km (7 mi).



Baker, 1982; Williams and Braunach, 1984; Williams and Fidler, 1985). The EM methods continue to be used in natural, agricultural, and oil field salinity mapping (McKenzie et al., 1997; Paine et al., 1997, 1999, 2006, 2007, 2009; Smith et al., 1997; Banerjee et al., 1998; Paine, 2003).

Airborne Geophysical Survey

A helicopter-towed FDEM instrument (the Geophex GEM-2A) measured apparent electrical conductivity of the streambed along 437 km (272 mi) of the upper Colorado River and a major tributary. Geophex, Inc., provided a GEM-2A instrument, a helicopter to tow the instrument, and a crew to acquire and process the data (Geophex, 2005). The GEM-2A is a towable tube that includes a single pair of transmitter and receiver induction coils in a horizontal plane that operate at multiple effective frequencies (and exploration depths) simultaneously (Won et al., 2003). Five primary instrument frequencies (450, 1350, 4170, 12,810, and 39,030 Hz) yielded skin depths (the depth at which the field strength generated by the transmitter coil is reduced to 1/e times its original value; Telford et al., 1990) ranging from a few meters at the highest frequency to several tens of meters at the lowest frequency. Skin depth is a crude estimate of the maximum exploration depth for a given frequency. Centroid depth provides a better depth estimate for the electric current system producing the secondary field at a given frequency. It is calculated as the real component of the complex transfer function relating frequency and orthogonal components of the horizontal electric and magnetic fields at the ground surface (Sengpiel, 1988; Sengpiel and Siemon, 2000). Average centroid depths for the Colorado River data increase with decreasing frequency (13 m [43 ft] at 39,030 Hz, 17 m [56 ft] at 12,810 Hz, 21 m [69 ft] at 4170 Hz, 26 m [85 ft] at 1350 Hz, and 33 m [108 ft] at 450 Hz).These values may be deeper or shallower than the actual exploration depth achieved (Spies, 1989; Reid and Macnae, 1999; Huang, 2005), depending mostly on the actual ground conductivity and conductivity structure. Apparent conductivities calculated at multiple frequencies and exploration depths can be gridded to produce an apparent conductivity pseudodepth section along the flight line (Figure 2), considering distance along the stream as one variable and apparent conductivity at each centroid depth as the other variable. These sections indicate whether apparent conductivity increases or decreases with exploration depth and depict the lateral extent and the relative depths of salinization.

Ground-Based Geophysical Measurements

Results of the airborne survey guided ground-based measurements of apparent conductivity along 12 lateral ground-surface transects (lines labeled 1 through 12,

Figure 3) using a Geonics EM34-3 ground conductivity meter at a 20-m (66 ft) transmitter-to-receiver coil separation and a primary frequency of 1600 Hz. At these settings, measured apparent conductivities are bulk values representing approximately the upper 10 to 12 m (33–39 ft) with the coils oriented in a horizontal plane and 20 to 25 m (66–82 ft) with the coils oriented in a vertical plane. These measurements helped determine the lateral extent of salinization within the effective exploration depth of the instrument.

Time-domain EM soundings at five locations (Figure 3) examined changes in ground conductivity to greater depths than those reached by water and monitoring wells that were typically less than 30 m (98 ft) deep. Subsurface conductivity profiles acquired using the TDEM method have lower resolution than those measured using borehole instruments but are useful proxies for boreholes where large contrasts exist between salinized and nonsalinized groundwater. The soundings were acquired using a Geonics PROTEM 47 instrument, a 40 × 40–m (131 × 131 ft) single-wire transmitter loop, transmitter currents of 1 to 2.5 A, current turn-off time of 2.5 μs, and transient decay recording times ranging from 7 μs to 7 ms after current turn-off. Time-domain EM data were processed using the software IX1D published by Interpex LTD.

Borehole Geophysical Logging

Borehole conductivity (EM) logs are useful in identifying high-conductivity strata that host highly saline water. Borehole EM logs produce detailed subsurface conductivity profiles that can be used to identify specific salinized units and other stratal boundaries. A Geonics EM39 probe measured apparent conductivity at 2.5-cm (0.98 in.) depth intervals in the uncased Mays 1 well and in polyvinyl chloride–cased monitor wells 1 through 9 (Figure 3). The effective radius of investigation for this instrument is 1.5 m (4.9 ft), sufficient to extend well into the material surrounding the borehole.

Passive gamma-ray probes, such as the Geonics Gamma 39 used in this study, respond to changes in mineral types and are used to identify subsurface lithologic boundaries and correlate geologic units. Nearly all natural gamma radiation is emitted by isotopes of potassium (K^{40}) and the uranium (U^{238}) and thorium (Th^{232}) decay series (Telford et al., 1990). Gamma response is proportional to concentrations of these radioactive isotopes in the logged material and is practically proportional to K_2O content, which is generally higher in clays than in siliceous sands (Schlumberger, 1989). Typical gamma-ray probes use a thallium-activated sodium iodide detector to record gamma count rates originating in the strata surrounding the borehole.

AIRBORNE STREAM-AXIS PROFILE

Results from the airborne geophysical survey flown along the axis of the Colorado River and a major tributary were used to screen the basin for highly salinized areas. These data helped delineate 11 conductive streambed segments that are interpreted to be areas where saline groundwater increases the salinity of the Colorado River (Paine et al., 2009). The Machae Creek area is the most upstream of four conductive streambed segments identified along the Colorado River axis between Spence and Ivie reservoirs (Figure 1). The river flows adjacent to Wendkirk oil field at the downstream end of the segment.

Airborne EM data from the Machae Creek segment of the Colorado River show elevated apparent conductivities at the shallowest exploring frequency (39,030 Hz) and at the two deepest exploring frequencies (450 and 1350 Hz). At the shallowest depths on a pseudodepth section constructed from multifrequency data (Figure 2), elevated conductivities are found between 2 and 5 km (1.2 and 3.1 mi) at the upstream end of the segment and between 10 and 14 km (6.2 and 8.7 mi) at the downstream end. These include areas where evidence of near-surface salinization exists and probably represent near-surface accumulations of saline pore water from local and upstream sources and from evaporative concentrations of dissolved solids. These very shallow accumulations may or may not be related to deeper local salinity sources because the river carries high-salinity water from sources farther upstream that can be concentrated by evaporation. Elevated conductivities evident in low-frequency, more deeply exploring data between about 9 and 14 km (5.6 and 8.7 mi) downstream (Figure 2) suggest that this is an area where saline groundwater degrades surface water quality. Wendkirk oil field straddles the Colorado River along this segment. On this basis, more intensive ground and borehole investigations were focused on this area to determine whether evidence exists for high salinities adjacent to the river and in Wendkirk oil field that could contribute salinity to the river through groundwater discharge.

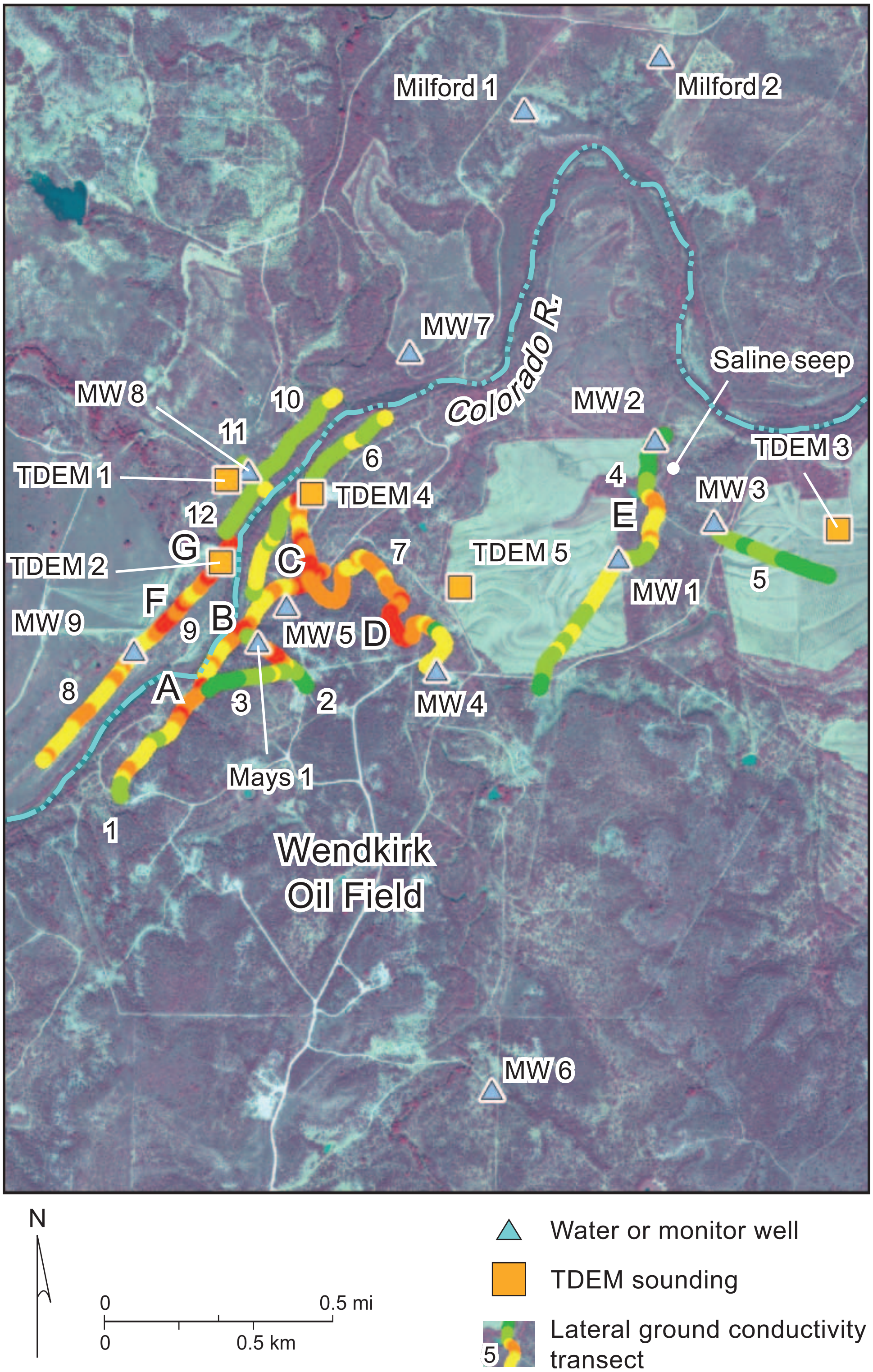


Figure 3. Locations of monitor and water wells, lateral ground conductivity (EM34) transects (1 through 12), TDEM soundings (TDEM1 through TDEM5), and interpreted salinized areas (A through G) in Wendkirk oil field on the Colorado River. Apparent conductivities on transects are color-coded such that orange and red indicate high conductivities and green and yellow indicate low to moderate conductivities in the horizontal plane coil orientation. Locations are superimposed on a 2004 aerial photograph provided by the Texas Natural Resources Information System. General location of the area is shown on Figure 1. TDEM = time-domain electromagnetic.

LATERAL GROUND CONDUCTIVITY TRANSECTS

At Wendkirk, apparent ground conductivity measurements acquired along 12 transects (Figure 3) identified local areas of elevated conductivity and delineated the lateral extent of salinized ground in the oil field within the exploration depth range of the instrument. Transects were placed parallel to the river (and topographically below the oil field) on both sides of the river to identify possible paths to the river, along a central ephemeral stream that drains a large part of the oil field south of the river to capture contributing sites to the stream, near possible salinity sources such as abandoned produced water pits, high-salinity water wells, and across an area east of the main oil field where saline water has been sampled in a seep and in monitor wells.

Transects Adjacent to the Colorado River

Transects north of the Colorado River extend more than 1.6 km (1.0 mi) on flood plain and alluvial terrace deposits (Figure 3). These lines cross the northern extension of the oil field and were placed to intercept possible shallow groundwater flow routes from the upland to the river. Two monitor wells (MW-8, total dissolved solids [TDS] = 23,200 mg/L; MW-9, TDS = 2600 mg/L) are within the transect area.

Transect 8 begins at monitor well 9 and extends southwestward more than 500 m (1640 ft) (Figure 3). Apparent conductivities are moderate to low, decreasing to the southwest. No significant salinization is expected to exist within the exploration range of this instrument southwest of monitor well 9, consistent with the relatively low salinity measured in this well. Transect 9 extends about 500 m (1640 ft) northeastward from monitor well 9 toward a creek (Figure 3). Two areas of elevated ground conductivity were identified north of the river that indicate the presence of shallow saline water (areas F and G, Figure 3).

Transects 10, 11, and 12 are near monitor well 8 (Figure 3). Transect 10, extending about 500 m (1640 ft) northeast of the well, depicts low to moderate conductivities that only increase within 100 m (328 ft) of a creek at the northeast end of the line (Figure 3). Similarly, the short transect southwest of monitor well 8 reveals low to moderate conductivities at the well and an increase approaching a creek south of the well (area G). The juxtaposition of high TDS concentrations in the well with relatively low apparent conductivities suggests that the instrument did not reach the depth of the salinized ground. Monitor well 8 is located on a high terrace above the Colorado River and was drilled deeper than other wells north of the river. The water level is 9 to 10 m (30–33 ft) below the ground surface, several meters deeper than the other monitor wells. At this well, saline water saturates deeper strata that are beyond the exploration depth of the EM34 at the 20-m (66-ft) coil separation.

On the south side of the river, transects 1 and 6 span about 1900 m (6200 ft) across Wendkirk oil field (Figure 3). Transect 1 begins north of monitor well 5, crosses the principal drainage through the oil field, and ends more than 1 km (0.6 mi) to the southwest (Figure 3). Measured conductivities generally decrease toward the southwest, but four elevated conductivity segments occur, indicating probable shallow salinization along the transect. These include a 200-m (656-ft) long segment centered on the Wendkirk oil field drainage (area C, Figure 3), a 200-m (656-ft) long segment northwest of the Mays 1 well (area B, Figure 3), a broad segment near the intersection with transect 3 that coincides with efflorescence-coated fractures and bedding planes on a San Angelo Formation outcrop (area A, Figure 3), and a 100-m (328 ft) long segment northwest of a well site at the southwestern end of the line.

Transect 6 begins between the Colorado River and monitor well 5 and extends northeastward parallel to the river a distance of about 800 m (2625 ft) (Figure 3). The only significant segment of elevated conductivity coincides with the creek that drains the main Wendkirk oil field area. Higher soil moisture, shallow water tables, and high salinities are expected in the shallow subsurface within the creek valley, each of which can increase ground conductivity.

Transects near a High-Salinity Well

Transects 2 and 3 were located to better define shallow salinization near a well (Mays 1, area B, Figure 3) where the highest groundwater salinities have been measured (TDS = 43,000 mg/L at the Mays 1 well). Both transects begin at or near a former brine pit salinity source that is located about 200 m (656 ft) southeast of the well. Measured conductivities along transect 2 are low southeast of the former pit, increase to a peak between the pit and the Mays 1 well, and then decrease northwestward from the well toward the edge of the upland above transect 1. Elevated conductivities between the pit and the Mays 1 well probably represent shallow salinity migrating from the pit source. Decreasing conductivities northwestward from the Mays 1 well indicate that salinity occurs deeper than the instrument can reach as the depth to water increases near the edge of the upland. Higher conductivities recur in this area (area B) at the base of the upland scarp along transect 1 (Figure 3), where depth to water is shallow.

Transect 3 extends westward about 300 m (984 ft) from the former discharge pit (Figure 3). Elevated conductivities are measured near the pit but generally decrease with distance from the pit. Conductivities begin to rise near the west end of the line with the approach to elevated conductivity area A.

Creek Transect through the Oil Field

Acquiring transects along creek and drainage axes is an efficient approach to identifying significant salinization within the drainage basins. Transect 7 was acquired to identify possible salinity sources along an ephemeral stream that drains much of the oil field south of the river (Figure 3). Measured conductivities are relatively high along this transect but diminish at the upstream end near monitor well 4. Relatively high conductivities are the result of high moisture content in stream sediments along with elevated pore-water salinities. Three segments have particularly high shallow conductivities, including (from downstream to upstream) the lower reach near the confluence with the Colorado River, a segment near monitor well 5 (area C, Figure 3), and a segment adjacent to an abandoned well site southwest of the creek (area D). Area D probably is a salinity source area.

Transects near a Saline Seep

Saline seeps are relatively common features in oil fields that have near-surface salinization. The EM measurements across these seeps help establish the extent of salinization and possible source directions. At Wendkirk, two transects (4 and 5) were acquired to examine salinity distribution around a saline seep surrounded by monitor wells 1, 2, and 3 northeast of the main oil field south of the Colorado River (Figure 3). Transect 4 extends southward from low-salinity monitor well 2 (TDS = 3240 mg/L), passing across the drainage upstream of the seep. Measured conductivities along transect 4 are very low (40 mS/m or less) north of the seep drainage in the vicinity of monitor well 2 but increase rapidly approaching the drainage. Highest conductivities are measured across the drainage and remain at moderate to high levels southward to high-salinity monitor well 1 (TDS = 19,000 mg/L). Measured conductivities decrease along the southmost 200 m (656 ft) of the transect. Elevated salinities in the shallow subsurface probably occur between the drainage and monitor well 1 as well as for a distance of about 400 m (1312 ft) south of the well. Decreasing conductivities at the south end of transect 4 suggest that the southern boundary of shallow salinization was reached. Salinity sources are either within the elevated conductivity segment or farther to the west in the main Wendkirk oil field area.

Transect 5 extends eastward about 500 m (1640 ft) (Figure 3) from high salinity monitor well 3 (TDS = 11,600 mg/L). Measured conductivities are moderate for a distance of about 200 m (656 ft) east of monitor well 3 but decrease significantly along the eastern 200 m (656 ft) of the transect. The moderate conductivity segment near monitor well 3 probably coincides with a shallow saline zone. The low conductivity segment at the east end of the line defines the eastern margin of the shallow saline zone.

LITHOLOGY AND SALINITY RELATIONSHIPS FROM BOREHOLE LOGS

Gamma and conductivity logs acquired in one water well (Mays 1) and nine monitor wells (Figure 3) helped (1) identify key lithologic boundaries between alluvial deposits and sandstone and mudstone bed rock and (2) delineate the vertical extent and intensity of salinization. Logging reached depths of 9 to 28 m (30–92 ft) in the monitor wells and 55 m (180 ft) in the Mays 1 well. No discernible relationship exists between the deepest elevation reached and the TDS concentration in water sampled from the well (Figure 4A), although the Mays 1 well penetrates to the lowest elevation (498 m [1634 ft] above mean sea level) and has the highest reported salinity among the Wendkirk area wells. Despite this, the preponderance of data suggests that variation in water salinity in the wells is not caused by increasing water salinity with depth reached by the wells, as might be expected if natural sources were the cause of high groundwater salinity.

Chloride-to-sulfate ratios vary widely among the well samples (Figure 4B) and may serve as a chemical discriminator for natural and oil field salinity sources. Dissolution of abundant sulfate minerals such as gypsum and anhydrite in shallow strata imbues local groundwater with naturally low chloride/sulfate ratios, but introduction of produced water with extremely high chloride/sulfate ratios greatly increases those ratios in impacted areas. Ratios are less than 1 in samples from relatively low-salinity wells (the Milford 1 and 2 water wells and monitor wells 2, 7, and 9, Figures 3, 4). Ratios are higher than 5 in high-salinity wells (Mays 1 and monitor wells 4, 5, and 6). Values for Colorado River samples in this area are between 1.7 and 2.6. Wells with ratios near or higher than about 1 may indicate preferential chloride contributions from produced water.

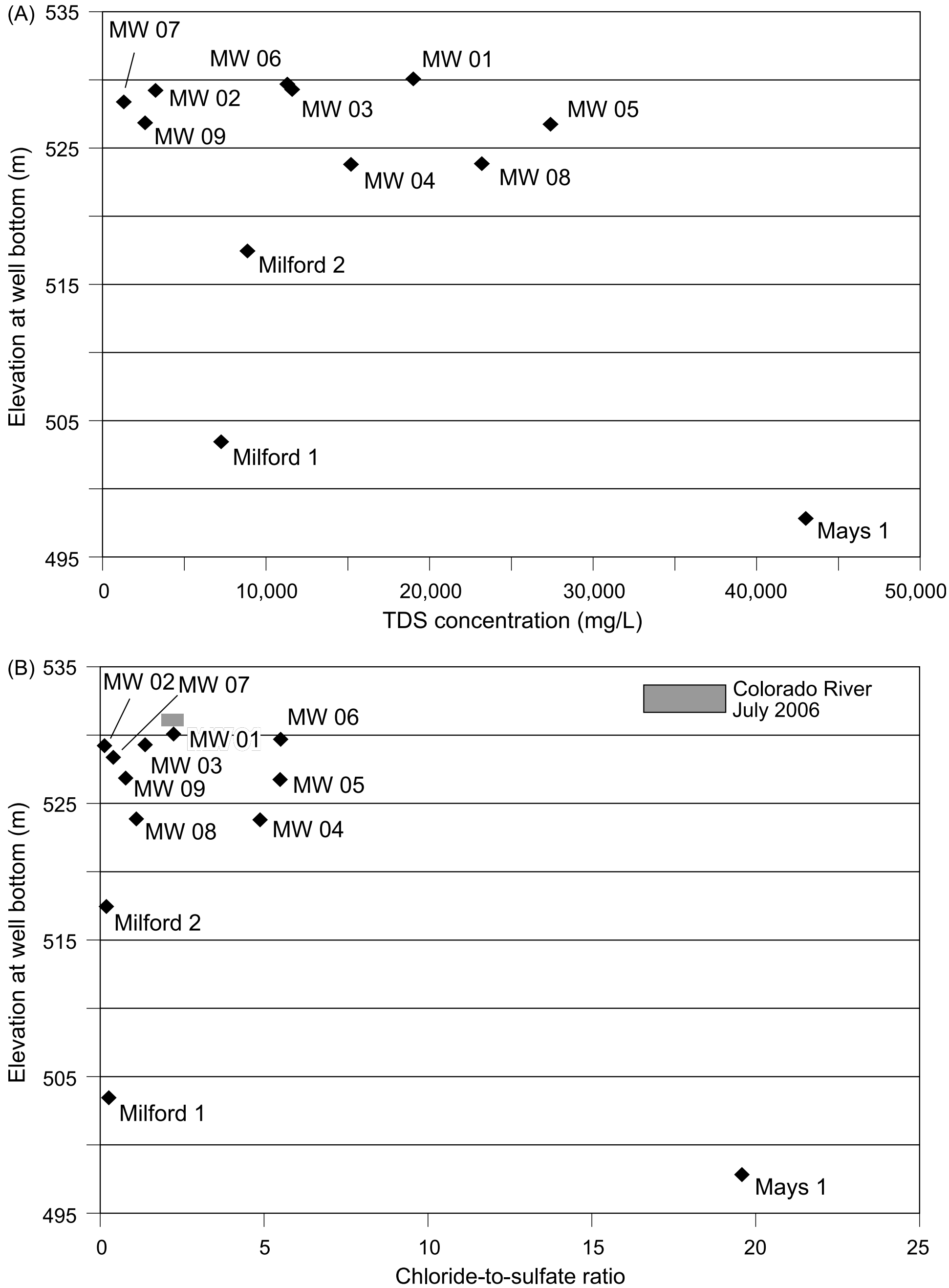


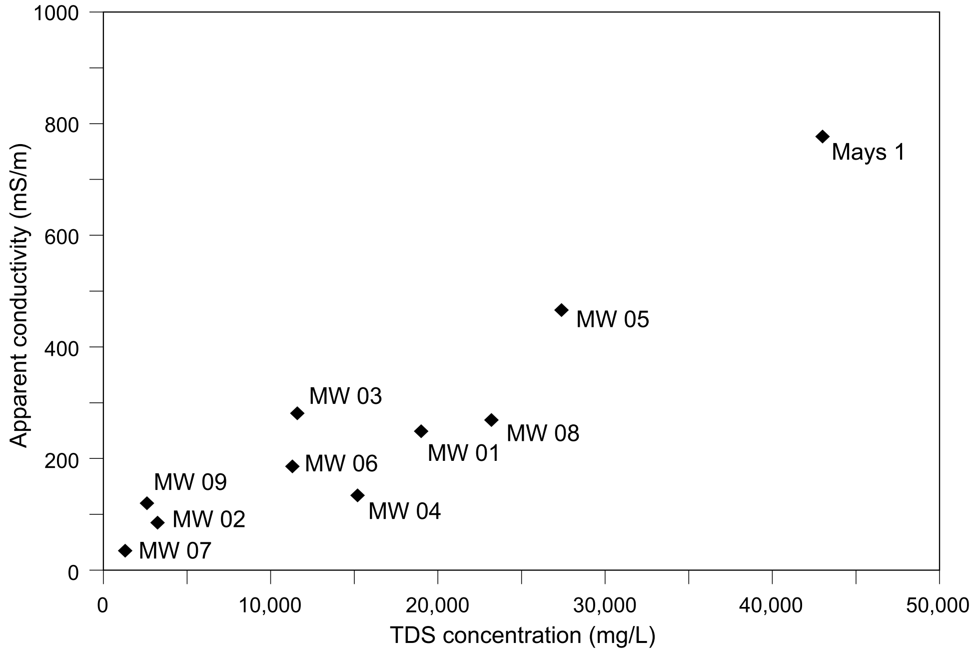
Figure 4. Relationship between (A) total dissolved solids (TDS) and (B) chloride-to-sulfate ratio in well water samples and elevation at the bottom of the well. Also shown are data for the Colorado River at Wendkirk oil field. Well and river sample data provided by TRC Environmental Solutions.

Measured apparent conductivities in the wells range from a few to about 800 mS/m. In all wells except the lowest-salinity monitor well, highest conductivities were measured below the water level. The effectiveness of measuring conductivity in salinity investigations is demonstrated by the relationship (r^2 = 0.88) between TDS concentration in well water samples and the maximum conductivity measured in the borehole logs (Figure 5). Logs in the low-salinity wells record the lowest maximum apparent conductivities (Figure 5) and also have the lowest choride:sulfate ratios (0.01–0.74, Figure 4B). High-salinity wells record the highest maximum conductivities and have very high chloride/sulfate ratios (5–20). Maximum recorded borehole conductivities increase with water salinity, as does the chloride/sulfate ratio.

Cross Section 1

Cross section 1 passes through the main oil field south of the Colorado River. It combines gamma and conductivity logs from four wells (Figures 3, 6) to illustrate lithologic and salinity relationships. All these wells have

Figure 5. Relationship between total dissolved solids (TDS) concentration in well water samples and maximum apparent conductivity measured in the same wells using a borehole conductivity probe. Water sample data provided by TRC Environmental Solutions.



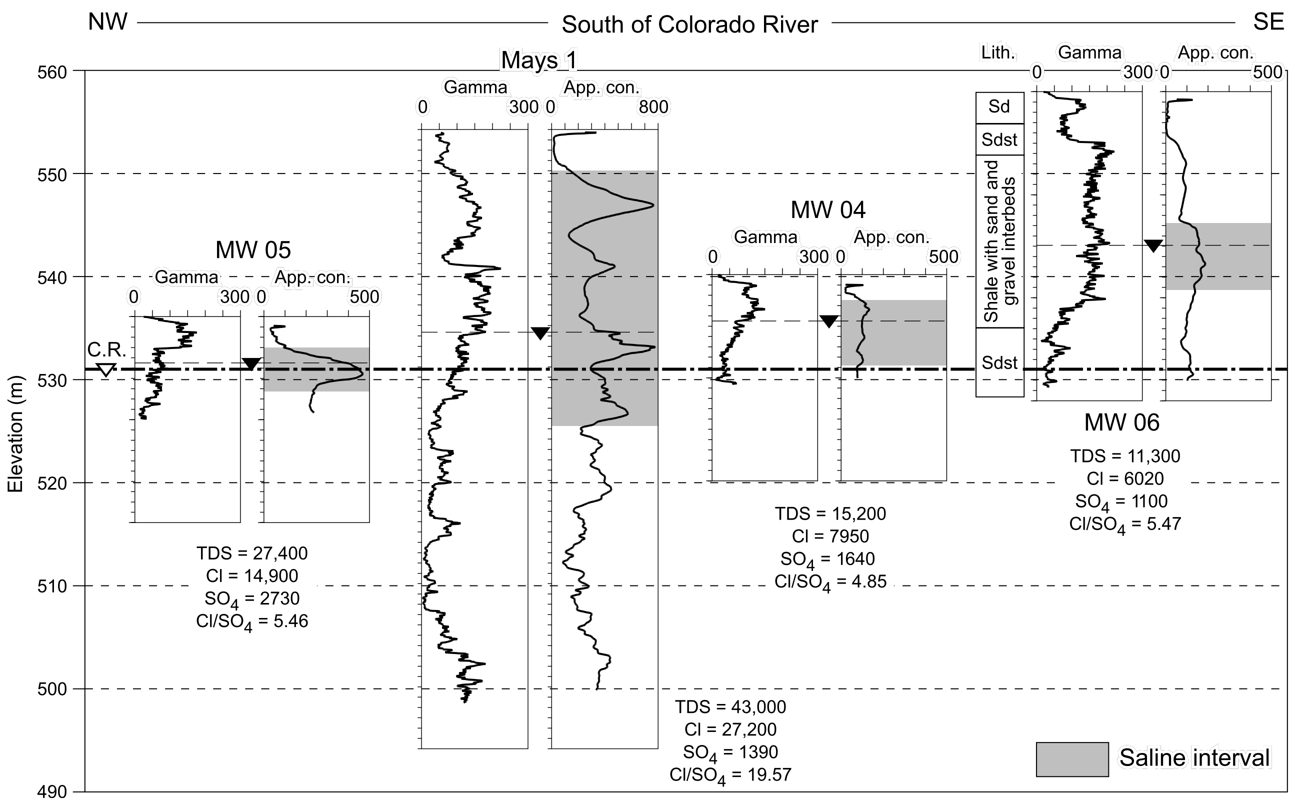


Figure 6. Conductivity and gamma log cross section 1 extending generally northwest to southeast on the south side of the Colorado River. Salinized intervals are shaded. Dashed line is approximate Colorado River water elevation. Chemical concentrations in milligrams per liter. Also shown is a representative lithologic log from well MW06 (sd = alluvial sand; sdst = San Angelo Formation sandstone) provided by TRC Environmental Solutions. Well locations are shown on (Figure 3). TDS = total dissolved solids.

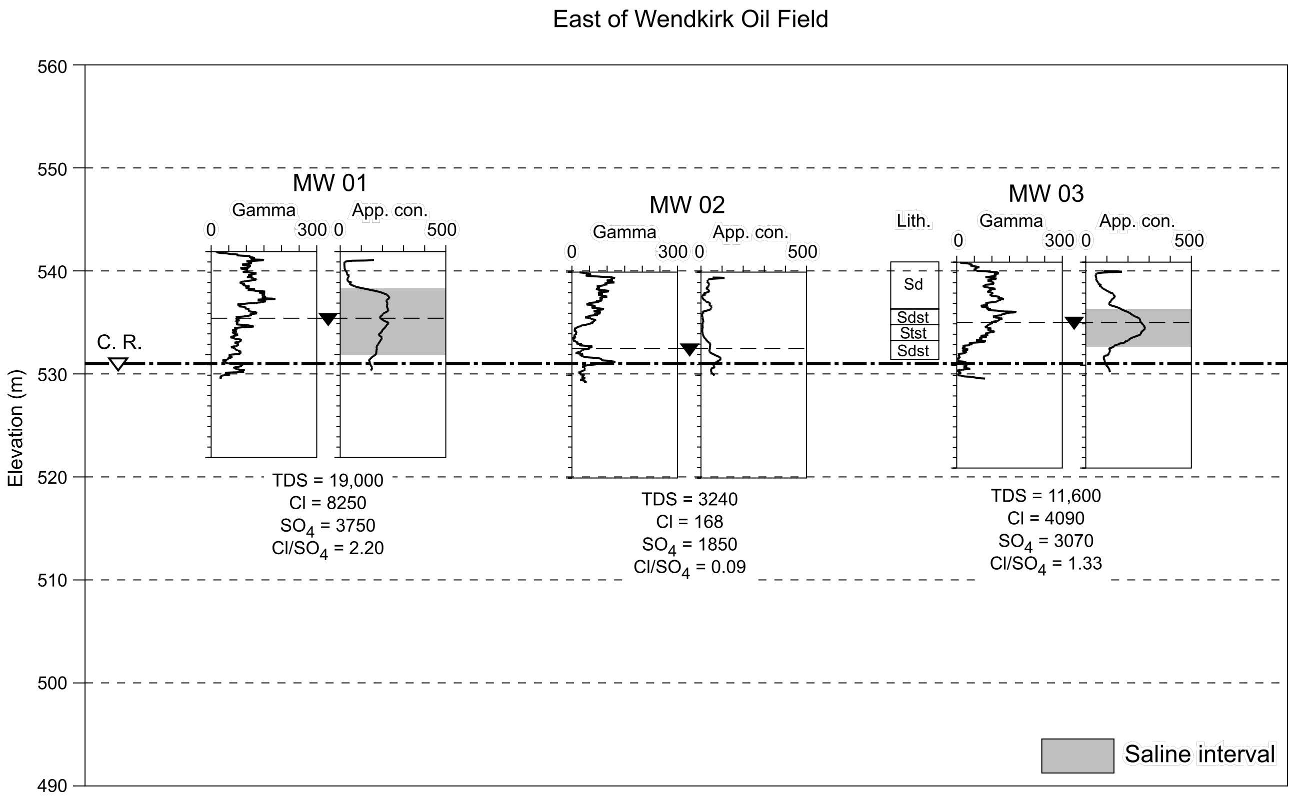


Figure 7. Conductivity and gamma log cross section 2 east of Wendkirk oil field and south of the Colorado River. Salinized intervals are shaded. Dashed line is approximate Colorado River water elevation. Also shown is a representative lithologic log from well MW03 (sd = alluvial sand; sdst, stst = San Angelo Formation sandstone, siltstone) provided by TRC Environmental Solutions. Well locations are shown on Figure 3. TDS = total dissolved solids.

high salinities (11,300–43,000 mg/L TDS). Chloride/sulfate ratios are also high, ranging from 4.85 to 19.6.

Gamma logs effectively distinguish boundaries between the alluvial and bedrock strata. Comparisons of gamma logs with lithologic descriptions made during drilling demonstrate that relatively coarse Colorado River alluvial and terrace deposits (dominantly sand, gravel, and silt) found at and near the surface have moderately high gamma count rates. All wells penetrate sandstone and mudstone bedrock units of the San Angelo Formation that have low gamma count rates in the sandstones and high count rates in the mudstones.

Conductivity logs respond strongly to water salinity. Moderate conductivities were measured in the wells farthest from the river. Much higher conductivities were measured in bedrock strata at and below the water level in monitor well 5, and in several stratal horizons in bed rock above and below the water level in the deeper Mays 1 well (Figure 6). These data suggest that at least four stratal horizons above and below the water level (including three above the Colorado River elevation) are salinized.

All four wells in cross section 1 show evidence of oil field salinization (anomalously high conductivities, salinities, and choride:sulfate ratios), but the salinization is most severe in the two wells nearest the river. Lateral and vertical infiltration of produced water from a former brine discharge pit is the most probable salinization mechanism for elevated conductivity area B (Figure 3).

Cross Section 2

Cross section 2 surrounds the saline seep area northeast of Wendkirk oil field south of the Colorado River (Figures 3, 7). Gamma and lithologic logs in these relatively shallow wells show moderately high gamma count rates associated with Colorado River alluvial and terrace silts, sand, and gravel that are 5 to 7 m (16–23 ft) thick. These deposits rest on San Angelo Formation sandstone, which have lower gamma count rates.

The highest apparent conductivities were measured in monitor wells 1 and 3. These wells also have high TDS concentrations (19,000 and 11,600 mg/L)

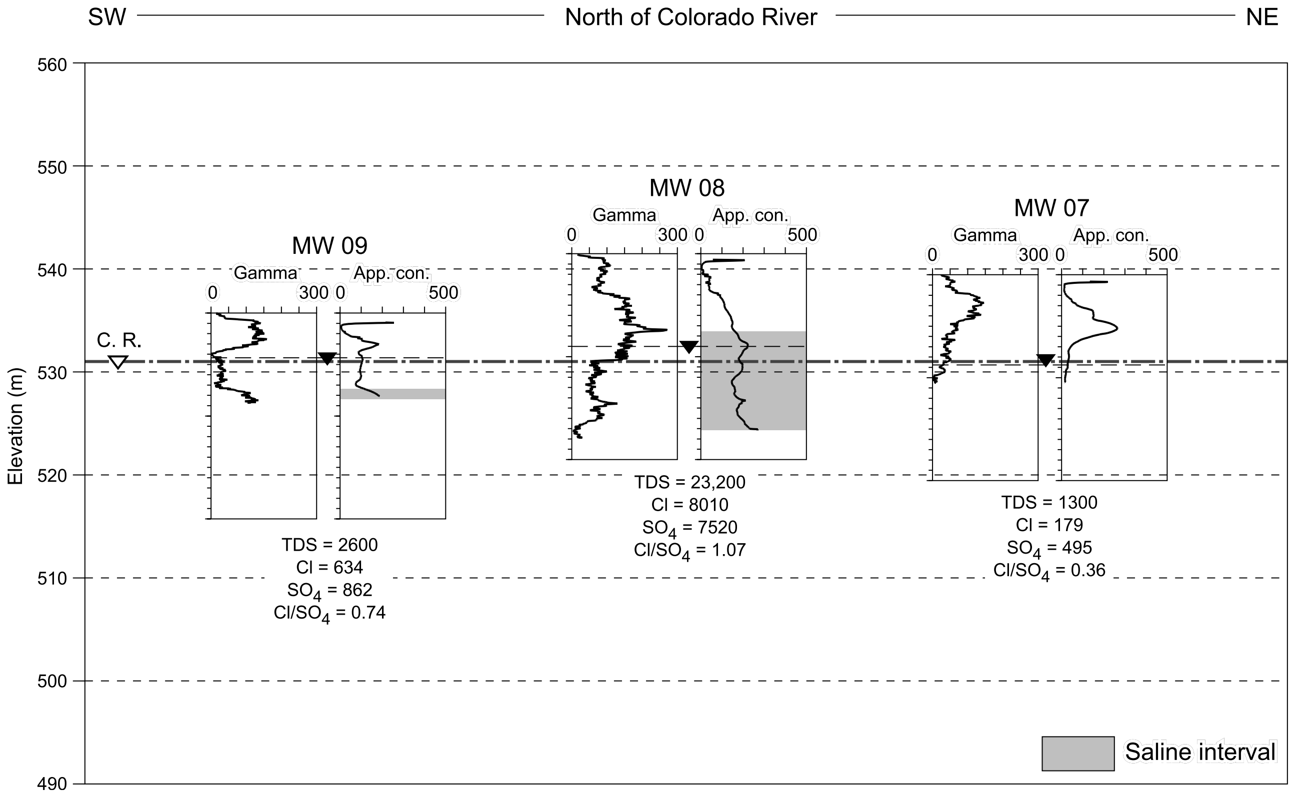


Figure 8. Conductivity and gamma log cross section 3 extending generally southwest to northeast on the north side of the Colorado River. Salinized intervals are shaded on the conductivity log. Dashed line is approximate Colorado River water elevation. Also shown is a representative lithologic log from well MW08 (sd = alluvial sand; sdst = San Angelo Formation sandstone) provided by TRC Environmental Solutions. Well locations are shown on Figure 3. TDS = total dissolved solids.

and chloride/sulfate ratios (2.2 and 1.3) compared with those in monitor well 2 (TDS = 3240 mg/L and chloride/sulfate = 0.09). Water-level elevation in monitor well 2 is also 2 to 3 m (7–10 ft) lower than elevations in monitor wells 1 and 3.

The abrupt change in conductivity, water salinity, chloride/sulfate ratio, and water-level elevation between monitor wells 1 and 3 (located south of the drainage feeding the saline seep) and well 2 (located north of the drainage) suggests that the drainage intercepts northward-flowing shallow saline groundwater between monitor well 2 and monitor wells 1 and 3, directing it eastward toward the seep and the confluence into the Colorado River.

Cross Section 3

Gamma and conductivity logs from three monitor wells form a southwest-to-northeast cross section north of, and parallel to, the Colorado River (Figures 3, 8). Gamma and lithologic logs show similar stratal relationships to those in wells south of the river (Figures 6, 7). Silty and gravelly sand forms Colorado River alluvial and terrace deposits that have moderately high gamma count rates and are 4 to 5 m thick. Alluvial deposits overlie San Angelo Formation sandstones (low gamma count rates) and mudstones (high count rates).

Measured conductivities at and below water levels in monitor wells 9 and 7 are low southwest and northeast of the Wendkirk oil field axis (Figure 8). Water samples from these wells have among the lowest salinities (TDS = 2600 and 1300 mg/L) and chloride/sulfate ratios (0.74 and 0.36) of the sampled wells. Higher conductivities were measured below the water level in monitor well 8 near the Wendkirk oil field axis, particularly at the deepest depth logged (17 m [56 ft]) that coincides with wet strata encountered during drilling. Salinities are high in this well (TDS = 23,200 mg/L); the chloride/sulfate ratio (1.07) is higher than those in other wells north of the river but is not as high as those in salinized wells south of the river and is lower than ratios for the Colorado River. The relatively small

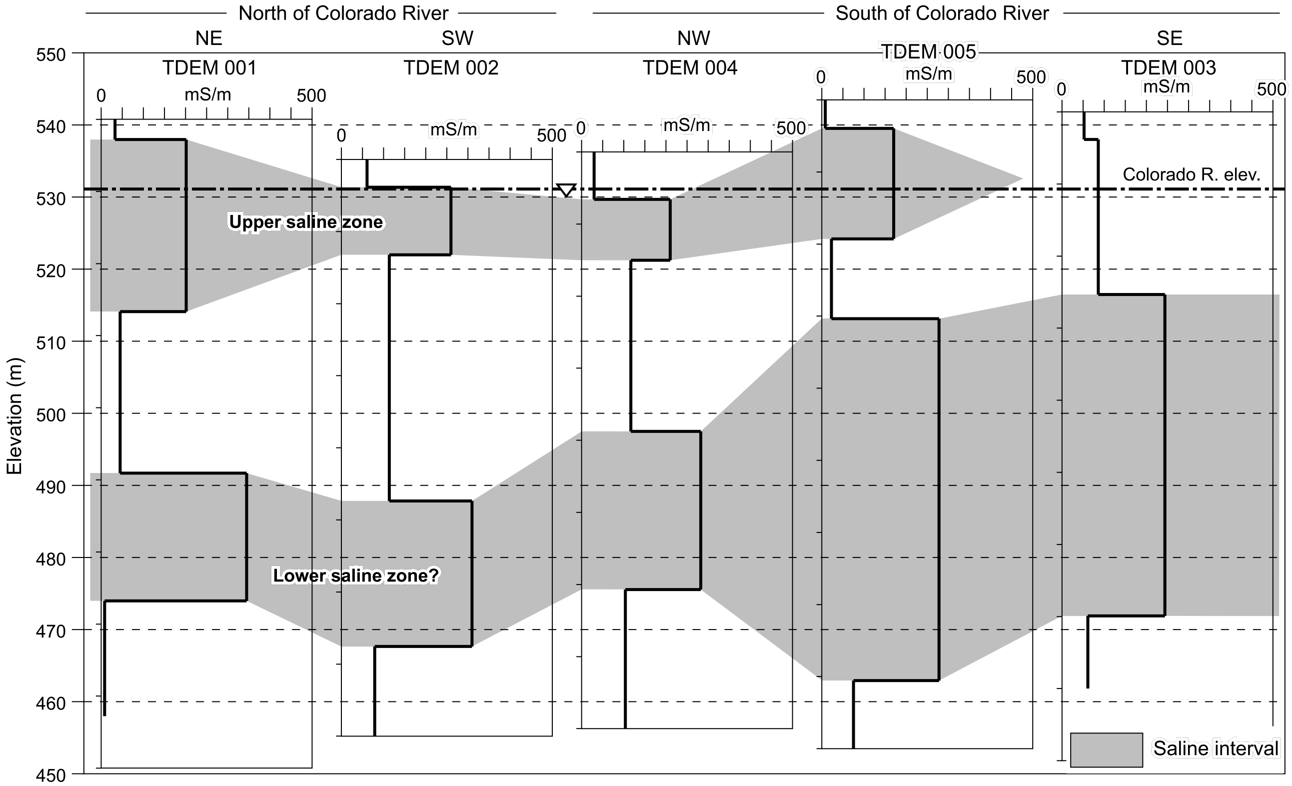


Figure 9. Best-fit conductivity models obtained from time-domain electromagnetic (TDEM) soundings north and south of the Colorado River (Figure 3). Dashed line is approximate Colorado River water elevation.

chloride enrichment suggests dominant natural (sulfate-rich) and perhaps minor oil field (chloride-rich) sources cause elevated salinities in this well.

TIME-DOMAIN ELECTROMAGNETIC SOUNDINGS

Five TDEM soundings (Figure 3) supplement the lateral transects and borehole logs by providing generalized conductivity profiles to greater depths than those reached by the transects and the wells. Three of these are located south of the river, forming a section extending eastward from near the Colorado River to east of the saline seep area. Two more are located north of the river.

Four- or five-layer conductivity models provided adequate matches to the transients at each location (Figure 9). Exploration depths reached at least 60 to 90 m (197–295 ft) to elevations 30 to 40 m (98–131 ft) deeper than those reached by the deepest logged well (Figure 6).

At all locations except one, the generalized conductivity structure includes, from shallow to deep, a thin poorly conductive surface layer a few meters thick; an upper conductive layer modeled at about 10 to 20 m (33–66 ft) thick; a poorly conductive layer 10 to more than 30 m (33 to >98 ft) thick; a lower conductive layer about 20 to 50 m (66–164 ft) thick; and a basal, poorly conductive layer of undetermined thickness (Figure 9). Sounding TDEM 3, located southeast of the seep area, is similar to the others, except that the shallow conductive layer is absent.

In all soundings, the thin poorly conductive surface layer represents relatively dry strata above the water table. In the soundings near the Colorado River (TDEM 2 and TDEM 4, Figure 9), the top of the upper conductive zone has an elevation near that of the Colorado River water level and probably represents the top of relatively saline, shallow groundwater sampled in the monitor wells. The elevation at the top of the upper conductive zone climbs in soundings farther from the river and at higher surface elevations (TDEM 1 and TDEM 5, Figure 9), again occurring at elevations similar to those of saline water levels in nearby monitor wells. The similarity in elevations and the high conductivities suggest that the upper conductive layer represents a shallow saline groundwater horizon in the area of the oil field. This shallow saline horizon is absent at TDEM 3, an area where measured ground conductivities along transect 5 (Figure 3) also suggest the absence of shallow saline water. The association of the upper saline zone encountered in all other soundings with the oil field along with elevated TDS concentrations and chloride/sulfate ratios in groundwater suggests an oil field salinity source.

The deeper conductive layer is present in all soundings and was reached by only the Mays 1 well (Figure 6). This is tentatively interpreted as a lower zone of saline groundwater that probably represents natural sources of salinity such as regional groundwater flow and related dissolution of Permian evaporite strata, although possible oil field sources (such as upward brine migration through boreholes) cannot be excluded by the available data.

CONCLUSIONS

Stream-axis airborne EM surveys are a rapid noninvasive approach to identifying discrete salinized streambed segments, where highly saline base flow degrades surface-water quality. Results from these surveys can focus more intensive ground and subsurface investigations of salinization and optimize characterization, monitoring, and remediation efforts. In this example from the upper Colorado River basin, airborne measurements identified four streambed segments where high ground conductivities indicated near-surface salinization. Subsequent investigations focused on one of these segments that included a 1950s oil field where surface discharge of coproduced brine occurred before Texas' no-pit order went into effect in 1969. Ground and borehole geophysical measurements in the oil field complemented airborne stream-axis data and groundwater investigations by (1) delineating the lateral and vertical extent of salinization, (2) identifying salinity sources, (3) enabling a better conceptual understanding of the salinization mechanism, and (4) guiding future monitoring and remedial activities.

Ground conductivity transects identified salinization boundaries and discrete salinized areas in and near an oil field within the exploration depth of the ground conductivity instrument. Analyses of water samples from the Colorado River and from shallow wells suggest oil field sources of salinity where apparent conductivities, TDS concentrations, and chloride/sulfate ratios are high relative to areas outside the oil field.

Borehole gamma logs demonstrated consistent and distinguishable natural gamma count rates within coarse alluvial (moderate count rates) and bedrock strata (high rates in shale and low rates in sandstone). These logs refine key stratigraphic boundary picks based on borehole cuttings descriptions. Borehole conductivity logs showed a strong relationship between water salinity and measured conductivity. These logs identified single and multiple subsurface salinized horizons in water wells and monitor wells in and near Wendkirk oil field.

Time-domain EM soundings complemented borehole logs by serving as borehole proxies between wells and determining conductivity profiles to greater depths than those reached by wells. Soundings identified a shallow conductive layer with an upper boundary at or above the Colorado River that is correlatable across the oil field. This layer represents an upper saline groundwater zone that water analyses, borehole logs, and lateral conductivity transects suggest has a strong oil-field salinity component. Time-domain EM soundings also identified a deeper conductive naturally salinized zone.

When combined, airborne, surface, and borehole EM measurements help focus oil field salinization studies, provide a minimally invasive means to delineate lateral and vertical extent and intensity of salinization, and identify salinity source areas.

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