Geophysical Investigations of Salinization along Petronila Creek, Nueces and Kleberg Counties, Texas

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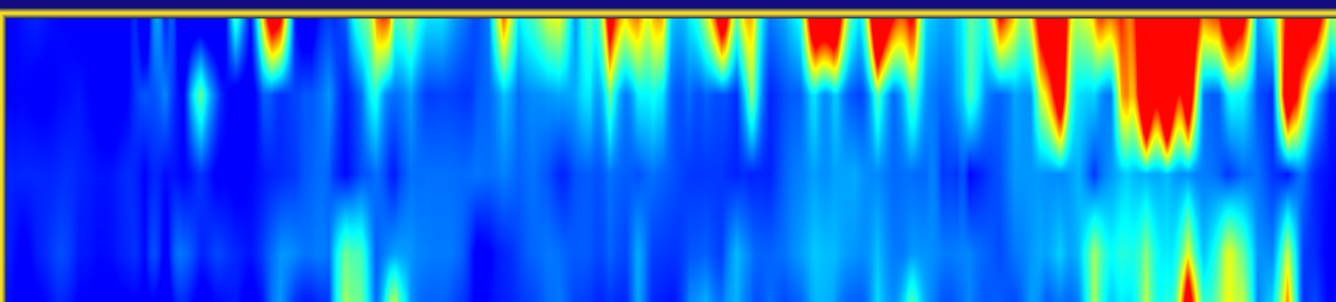

GEOPHYSICAL INVESTIGATIONS OF SALINIZATION ALONG PETRONILA CREEK, NUECES AND KLEBERG COUNTIES, TEXAS

by

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SUMMARY

We conducted an airborne geophysical survey, supporting ground-based measurements, and surface-water analyses to determine the extent of ground salinization, salinity sources, and migration mechanisms that elevate Petronila Creek (segment 2204) total dissolved solids (TDS), chloride, and sulfate concentrations beyond surface water quality standards for those constituents. Petronila Creek flows generally southeastward about 70 km on the coastal plain of south-central Texas before emptying into the Baffin Bay estuarine complex. Petronila Creek is fresh upstream from U.S. 77. TDS, chloride, and sulfate concentrations abruptly rise near U.S. 77, remaining high along the length of the stream.

Reconnaissance ground-based geophysical measurements showed elevated electrical conductivities associated with salinized ground along the creek and tributary drainage ditches. The airborne survey, conducted in February 2005, measured apparent electrical conductivity of the ground along a single flight line following Petronila Creek and within a 6 × 25 km area centered on the creek and extending from background areas northwest of U.S. 77 to below the point along the creek where estuarine mixing occurs. Results of the survey included maps at multiple exploration depths depicting apparent conductivity variations across the area and vertical sections along the creek axis depicting apparent conductivity changes with exploration depth. We used these data to identify three areas along Petronila Creek (the Driscoll, Concordia, and Luby areas) where high apparent ground conductivities indicate that near-surface salinization is likely to be increasing the TDS, chloride, and sulfate load of the creek.

Highly elevated conductivities at shallow exploration depths along Petronila Creek in the Driscoll and Concordia areas are associated with extensive adjacent conductive areas in the Driscoll Oil Field and along drainage ditches that carried highly saline water produced from the oil field before surface discharge was ended in 1987. These high-conductivity areas indicate the presence of near-surface salinization dominantly caused by past discharge of produced brine into ditches and pits, infiltration into sandy, permeable horizons visible in ditches and in subsurface

core, lateral migration in the shallow subsurface toward the creek, and eventual discharge into the creek at seeps or as shallow baseflow contributions. Flow measurements and chemical analyses of Petronila Creek coincident with the airborne survey show that the TDS load increased more than 20,000 kg/day in the Driscoll segment and 61,000 kg/day in the Concordia segment. Similar proportional increases were calculated for chloride and sulfate load.

The Luby area coincides with the zone of estuarine mixing at the downstream limit of the survey area. Conductivity patterns indicate a local area of near-surface salinization associated with a tributary and ditch system that drains the Luby Oil Field. Salinization evident at deeper exploration depths is interpreted to be the result of landward, subsurface intrusion of sea water.

Geophysical data and chemical analyses suggest that the dominant source of salinity in Petronila Creek between U.S. 77 and the estuarine-influenced zone is brine produced from local oil fields (Clara Driscoll, North Clara Driscoll, and Luby) and discharged into ditches before the Railroad Commission of Texas (RRC) ended that practice in 1987 or into pits before RRC's no-pit order was implemented in 1969. Airborne geophysical data suggest that there are extensive areas of salinization between the drainage ditches and the creek that may provide continuing sources of salinity along the Driscoll, Concordia, and Luby segments of Petronila Creek.

INTRODUCTION

We used ground-based and airborne geophysical instruments to measure the apparent electrical conductivity of the ground along and near Petronila Creek, Nueces and Kleberg Counties, Texas (fig. 1), to investigate the extent and intensity of salinization degrading surface water quality in the creek. This work follows previous investigations of surface-water quality by the Nueces River Authority and the Texas Commission on Environmental Quality (TCEQ, formerly TNRCC) and its subcontractors, including The Louis Berger Group and EA Engineering, Science, and Technology, resulting from the failure of Petronila Creek (segment 2204) to meet surface water quality standards for total dissolved solids (TDS), chloride, and sulfate (EA Engineering, Science, and Technology, 2002).

Petronila Creek (segment 2204) formally begins at the confluence of Agua Dulce Creek and Banquete Creek west of Robstown in Nueces County. It flows generally southeast for about 70 km across Nueces County and into Kleberg County, where it ultimately empties into Alazan Bay, part of the Baffin Bay estuarine complex. The creek flows in a narrow, relatively shallow valley eroded into clay-rich and sandy clay strata mapped as the Beaumont Formation (Brown and others, 1975), a late Pleistocene alluvial complex that slopes gently gulfward. Thin Holocene alluvial deposits (fine sand to clay) are present within the valley adjacent to Petronila Creek and in the streambed in places atop stiff Beaumont clay strata. Outside the valley, more recent flood and wind-blown (eolian) sediments blanket older Beaumont strata.

Recent chemical analyses of surface water in Petronila Creek, its tributaries, and in drainage ditches indicate that TDS and chloride concentrations are low upstream from the U.S. 77 bridge at Driscoll, but increase to levels that commonly fail to meet surface water quality standards downstream from U.S. 77 (figs. 2 and 3). Possible sources of the downstream increase in salinity include (a) the presence of primary saline pore water in Beaumont Formation strata that were deposited in a late Pleistocene coastal environment; (b) salt particles blown inland and deposited by prevailing onshore winds; (c) extensive inland flooding of saline gulf and estuarine water during recurrent tropical storms; and (d) surface and near-surface discharge of saline water during hydrocarbon exploration and produc-

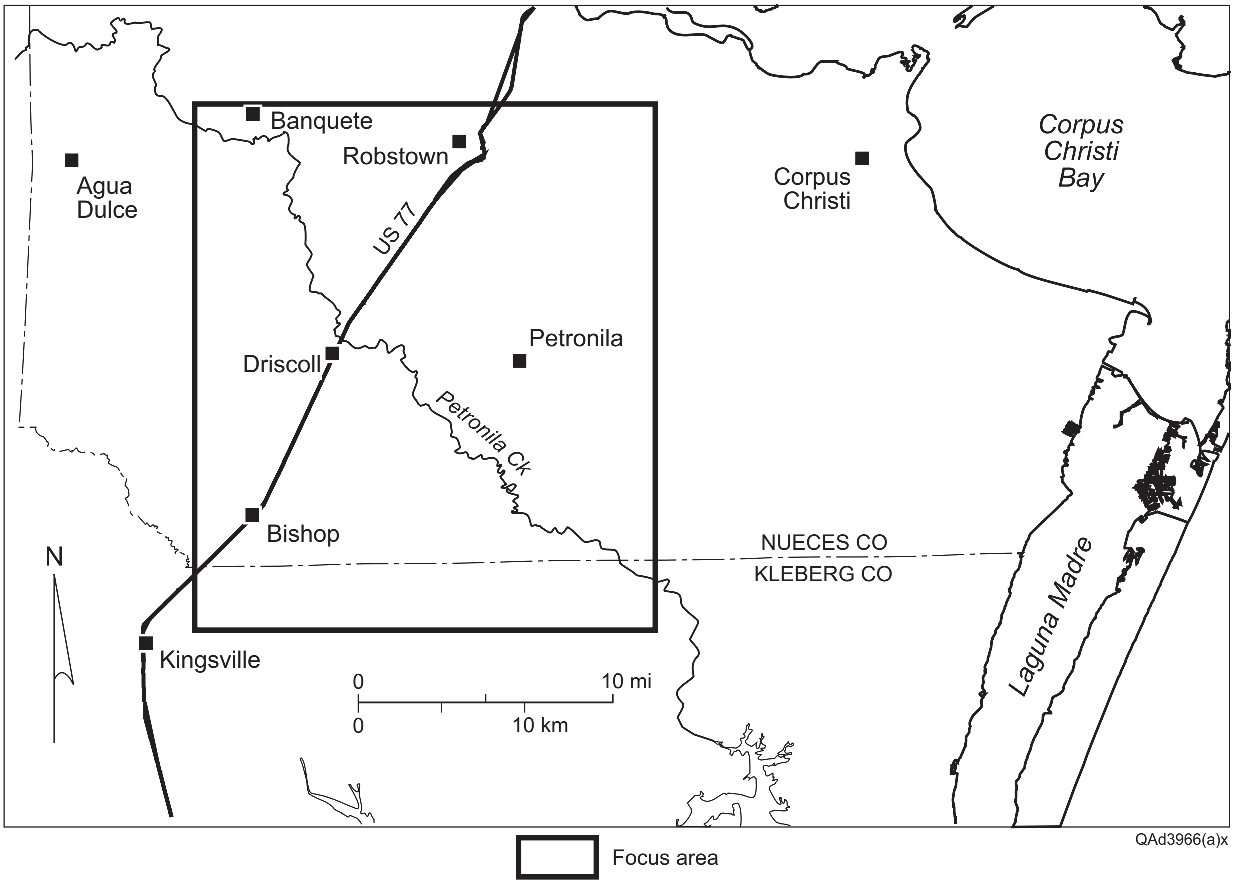

Figure 1. Map of the Petronila Creek region, Nueces and Kleberg counties, Texas.

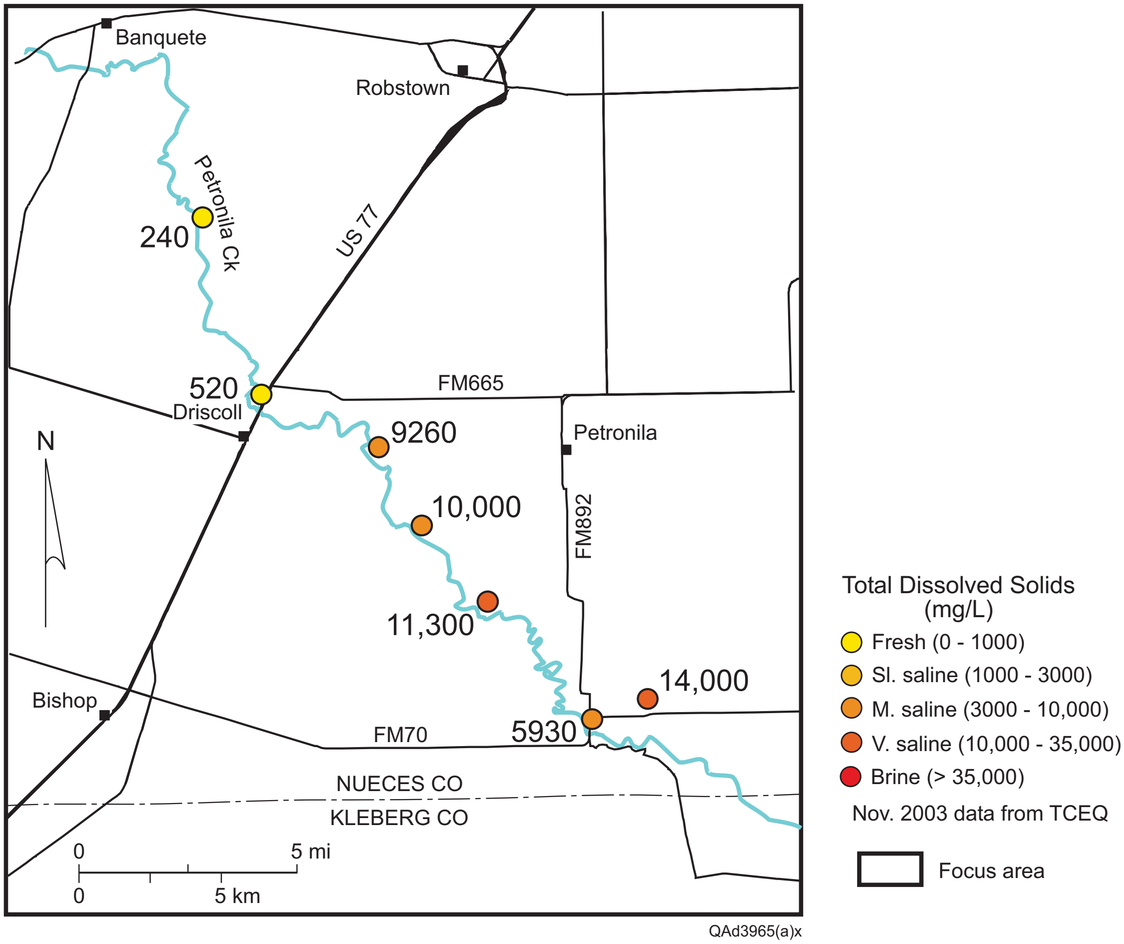

Figure 2. Map of the Petronila Creek area depicting total dissolved solids (TDS) concentration along the creek in November 2003. TDS data from the Texas Commission on Environmental Quality (TCEQ).

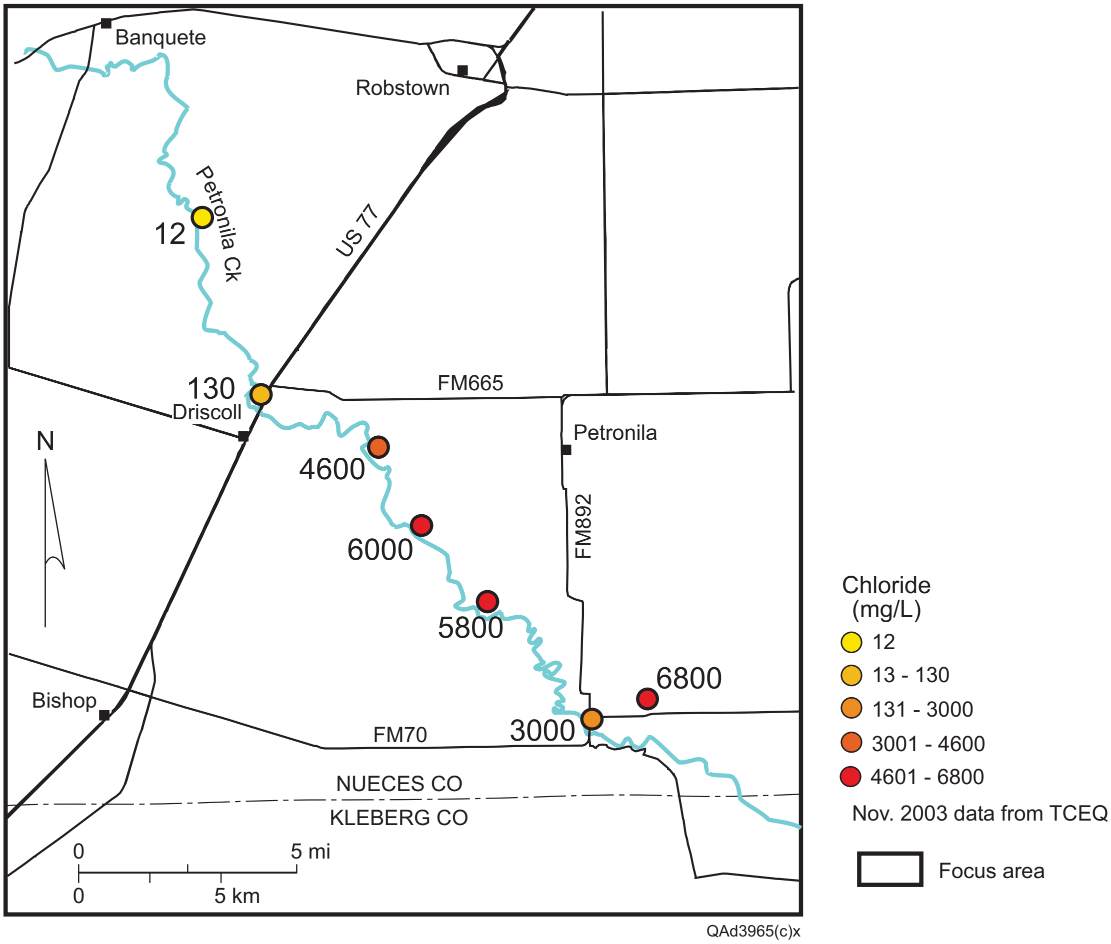

Figure 3. Map of the Petronila Creek area depicting chloride concentration in surface-water samples along the creek in November 2003. Chloride concentration data from TCEQ.

tion, including discharge and infiltration into brine pits, direct discharge into creeks and ditches, and perhaps leaking injection or brine-disposal wells. There has been significant oil and gas exploration and production activity in the study area; as of September 2001, there were 1,897 documented oil and gas wells in Nueces County (EA Engineering, Science, and Technology, 2002). Active or once-active fields on or adjacent to the creek include the Clara Driscoll, North Clara Driscoll, and Luby oil fields (fig. 4). Records from the Railroad Commission of Texas (RRC) indicate that 900 wells have been drilled within the boundary of the airborne geophysical survey. These include 359 active or plugged oil wells, 113 active or plugged gas wells, 215 active or plugged oil and gas wells, 187 dry holes, 16 injection or disposal wells, and 10 sidetrack wells. Produced brine discharge into surface pits presumably ceased with the implementation of the RRC's no-pit order in 1969. The RRC no longer permitted discharge of produced water to area drainage ditches and streams beginning in 1987 (Shipley, 1991). Water produced from area oil fields is highly saline; Gaither (1986) reports a TDS concentration of 49,300 mg/L and a chloride concentration of 28,904 mg/L in water produced from the Vicksburg Formation in the Clara Driscoll Oil Field. Shipley (1991) cites chloride concentrations of 36,500 to 55,700 mg/L in raw produced brines from the Petronila Creek area.

The past oil industry practice of discharging highly saline produced water at the surface into drainage ditches, pits, and Petronila Creek has been shown to have degraded surface-water quality and affected aquatic species in Petronila Creek (Shipley, 1991). In a study covering seven years of produced brine discharge directly or indirectly into the creek and one year of monitoring after permitted discharge ceased in 1987, Shipley (1991) showed that (a) creek salinities remained high below U.S. 77 after discharge ceased, except at the most upstream station monitored; and (b) pore-water salinities in creek-bottom sediments along the affected segment also remained high after discharge ceased, despite flushing storm events. Further, the chemical signature of saline Petronila Creek water more closely matched that of discharged produced water than that of saline Baffin Bay water downstream.

In addition to surface-water sampling and analysis, we can use geophysical instruments to noninvasively identify salinized ground that might contribute to the elevated salinity of Petronila Creek. The electrical conductivity of the ground (McNeill, 1980a) is generally dominated by electrolytic flow of

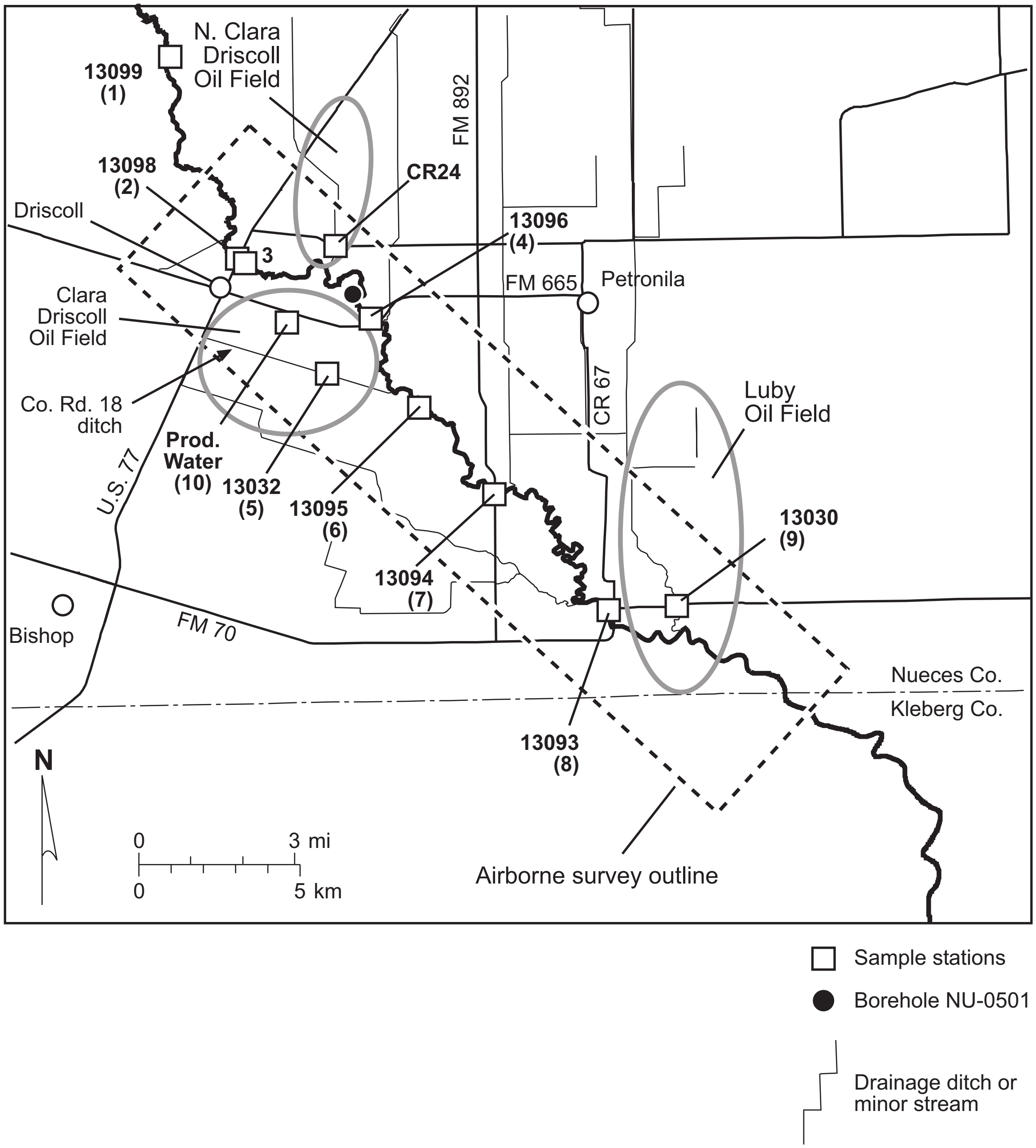

Figure 4. Map of Petronila Creek showing oil fields (gray), surface- and produced-water sample locations (appendix B), and the airborne survey outline (dashed). Also shown are drainage ditches (light lines) that discharge into Petronila Creek.

ions in pore water. Because the salinity of water is strongly correlated to its electrical conductivity (Robinove and others, 1958), the electrical conductivity of soil and sediment is also strongly influenced by the salinity of pore water. As pore-water salinity increases, so does the electrical conductivity of the ground. Our goal was to first use ground-based instruments in representative environments to acquire reconnaissance ground-conductivity data that would (a) supplement site-specific water-quality data, (b) establish background conditions in nonsalinized areas, and (c) determine the general extent of salinization along and near the creek. We then used results from the ground measurements to design an airborne geophysical survey that enclosed key Petronila Creek areas, including the oil fields, a nonsalinized upstream segment of Petronila Creek, and the major drainage ditches (fig. 4) that, along with Petronila Creek, received produced water from area oil fields until the practice was no longer permitted (Shipley, 1991). The airborne survey was intended to delineate the extent and assess the intensity of salinization in the area by measuring apparent ground conductivity at multiple exploration depths simultaneously. Finally, we combined lateral and vertical salinization patterns evident from airborne survey data with chemical analyses of surface water to interpret likely salinity sources and transport mechanisms that continue to produce high concentrations of TDS, chloride, and sulfate more than 15 years after permitted discharge ceased.

METHODS

We integrated ground-based and airborne geophysical measurements of the electrical conductivity of the ground with new and previously acquired surface-water chemistry data to delineate the lateral and vertical extent of salinization, assess possible salinity sources, and understand transport and discharge modes that have increased the salinity, chloride, and sulfate concentrations of Petronila Creek.

Ground-Based Electromagnetic (EM) Survey

We supplemented available surface-water quality data with measurements of the electrical conductivity of the ground in an attempt to identify critical stream segments where highly salinized ground may contribute to the degradation of surface-water quality. Where possible, we acquired ground-conductivity measurements along the axis of main and tributary streams. If the stream axis was not accessible, we measured ground conductivity along the stream bank. At most sites, stream access was by foot from road or bridge crossings. A hand-held GPS receiver provided locations for all ground-conductivity measurements.

We used the frequency-domain electromagnetic induction (EM) method to measure apparent electrical conductivity of the ground in the study area. Frequency-domain EM methods employ a changing primary magnetic field created around a transmitter coil to induce current to flow in the ground or in the annulus around a borehole, which in turn creates a secondary magnetic field that is sensed by the receiver coil (Parasnis, 1986; Frischknecht and others, 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.

We used a Geonics EM31 ground conductivity meter (fig. 5) to measure the apparent conductivity of the ground. This instrument operates at a primary EM frequency of 9.8 kHz, measuring apparent conductivity to a depth of about 3 m (horizontal dipole [HD] orientation) and 6 m (vertical dipole [VD] orientation) using transmitter and receiver coils that are separated by 3.7 m. The instrument has a useful conductivity range of less than 1 millisiemen/m (mS/m) to 1,000 mS/m.

Figure 5. Geonics EM31 ground conductivity meter measuring apparent conductivity in the drainage ditch along County Road 18 near Driscoll, Texas.

We acquired ground conductivity measurements at 165 locations along Petronila Creek, accessible tributaries, and drainage ditches that flow into Petronila Creek and across adjacent fields (appendix A) in June 2004. At most sites, we acquired several measurements at regular or irregular spacing depending on site accessibility.

The EM31 was calibrated at the beginning of each field day. Measurements of apparent ground conductivity were acquired by (1) placing the instrument on the ground (or holding it just above the surface of the water) in the vertical dipole orientation; (2) noting the apparent conductivity reading; (3) rotating the instrument into the horizontal dipole mode; (4) noting the apparent conductivity reading; and (5) obtaining a latitude and longitude coordinate for the measurement using the GPS receiver. All conductivity measurements were entered into a geographic information system database (ArcMap by ESRI) for analysis and comparison with other types of spatial data.

Airborne Geophysical Survey

We used an airborne implementation of the frequency-domain EM method to measure apparent electrical conductivity of the ground along the axis of Petronila Creek and within a corridor centered on Petronila Creek. Geophex provided the technical survey crew and their GEM-2A airborne instrument (fig. 6). Airlift Helicopters provided the flight crew and helicopter to tow the instrument.

The GEM-2A is an EM instrument that employs a single pair of transmitter and receiver induction coils in horizontal coplanar orientation that operates at multiple effective frequencies (and exploration depths) simultaneously (Won and others, 2003). We chose to use five primary frequencies: 450, 1350, 4170, 12,810, and 39,030 Hz (table 1), that yield exploration depths ranging from a few meters at the highest frequency to several tens of meters at the lowest frequency. EM calibration procedures included recording ambient noise at the chosen primary frequencies and pre- and post-flight checks of instrument phase response using a ferrite rod and amplitude response using a Q-coil. Instrument response and drift were compensated by raising the instrument above 300 m at the beginning and end of each flight to minimize the instrument's response to the ground.

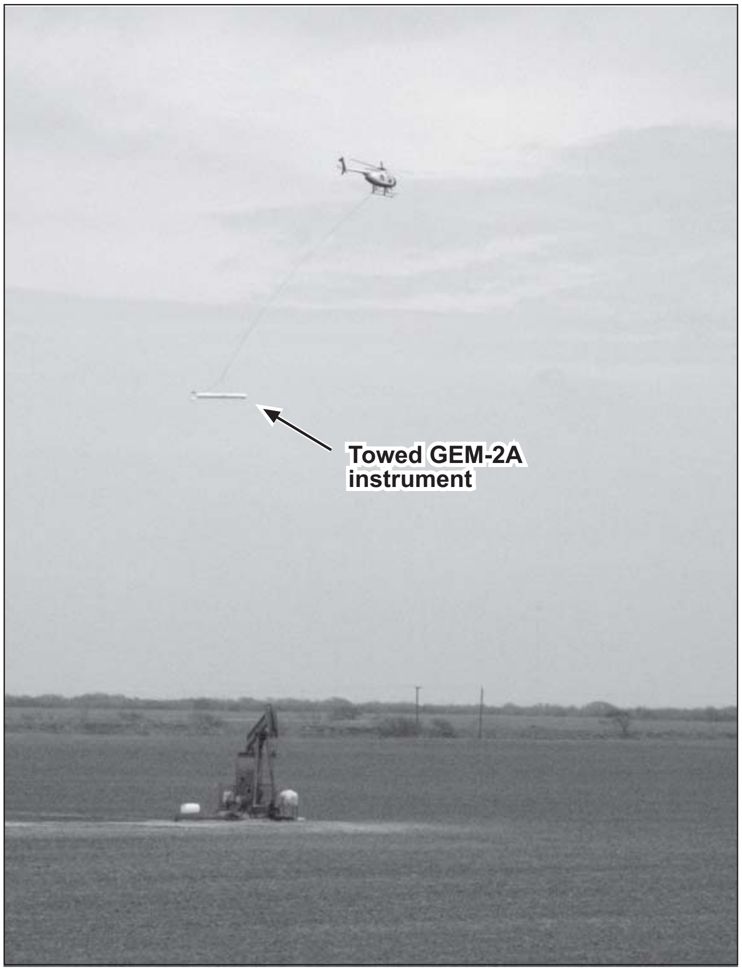

Figure 6. Hughes 369D helicopter towing the Geophex GEM-2A at survey height over the Clara Driscoll Oil Field southeast of Driscoll, Texas, February 5, 2005.

Table 1. Summary of acquisition parameters for the airborne geophysical survey of the Petronila Creek area flown by Geophex, Ltd. (Geophex, 2005).

Dates	February 5–6, 2005	
Aircraft	Helicopter, Hughes 369D	
Flight height	60	m
Flight speed (average per flight)	106 to 130	km/hr
Flight lengths (total)	879	km
Petronila Creek block (6 × 25 km, 200-m line spacing)	841	km
Petronila Creek axis	38	km
EM instrument	GEM-2A	
Bird height	30	m
Frequencies (5)	450, 1350, 4170, 12,810, 39,030	Hz
Sample rate and spacing	10	Hz
Sample spacing (average)	2.9 to 3.6	m
Magnetometer (airborne)	Cesium vapor, Geometrics G823A	
Height	30	m
Sample rate	10	Hz
Sample spacing (average)	2.9 to 3.6	m
Sensitivity	0.01	nT
Magnetometer (ground)	Cesium vapor, Geometrics G858	
Sensitivity	0.1	nT
Sample rate	1	Hz
Navigation	Differential GPS, receiver mounted on bird	

Also included in the instrument (table 1) are a cesium-vapor magnetometer that measures the strength of the Earth's magnetic field and a GPS receiver that provides the location of the instrument to an accuracy of 5 m or better. The helicopter flew at a nominal height of 60 m, towing the instrument at a height of about 30 m. Barometric and radar altimeters were installed in the helicopter to provide flight-height data. Altimeter height was combined with the length and orientation of the tow cable to calculate the height of the instrument above ground. The final sampling rate for EM and magnetic field data was 10 Hz. Average flight speeds of 106 to 130 km/hr translate to an approximate on-the-ground sample spacing of 3 to 4 m.

Geophex acquired airborne EM and magnetic field data along a total distance of more than 879 km in the Petronila Creek area on February 5 and 6, 2005. This distance included (a) a single line 38 km long along the axis of Petronila Creek between a point 4 km above U.S. 77 to a point 2 km beyond the Nueces–Kleberg county line, and (b) 841 km within a 6 × 25 km corridor centered on Petronila Creek in the same area as the axial line (fig. 4). We flew 31 NW–SE main lines spaced 200 m apart and 11 NE–SW tie lines spaced 2 km apart to provide detailed spatial coverage.

Geophex processed the airborne survey data to calculate apparent conductivities and depths along the flight lines for each frequency using a half-space model algorithm (Sengpiel, 1988; Geophex, 2005). We produced apparent conductivity images at each frequency along the stream axis by classifying values according to their mean and standard deviation for the stream segment. We also generated stream-axis pseudo cross sections (pseudosections) in selected areas using the data processing software ERMapper, considering distance along the stream as one variable and apparent conductivity at each frequency as the other variable. These sections are useful for depicting the lateral extent of salinization and the relative depths of likely salinity sources.

For the Petronila Creek block survey, we gridded apparent conductivity data using ERMapper to produce apparent conductivity maps for each frequency. These data were gridded using a 25 m cell size and triangulation interpolation between grid points. The five apparent conductivity measurements at each of the 214,081 measurement locations in the Petronila Creek block were used to create the grid images at each of the five frequencies, which were then imported into a GIS data base for analysis.

Water Conductivity, TDS, and Hydrochemical Analyses

Supplemental TDS measurements and surface-water sampling were completed during and after the airborne geophysical survey. For these activities, field locations were determined using a hand-held Garmin GPS receiver. Field measurements of stream water for specific electrical conductivity (SC), pH, and temperature were performed using a Hydrolab Quanta multiparameter probe system. Calibrations for SC and pH were performed with certified calibration solutions. Measurements with the Quanta were occasionally compared to measurements of the same samples performed with Oakton Con (SC) and Orion 250A+ (pH) laboratory instruments.

Nine stream samples and one produced-water sample were collected for laboratory analysis following protocols provided by the Kansas Geological Survey (KGS) where the analyses were performed (Donald Whittemore, pers. comm., 2005). The produced water sample (fig. 4; appendix B) was collected in October 2005 from a tank battery in the Clara Driscoll Oil Field that contained commingled brine produced from Vicksburg reservoir wells. Two splits were acquired for each sample. For major anion analyses, 500 ml of water was passed through a 0.45 mL Whatman syringe filter and collected in a 500-ml nalgene bottle that had been rinsed with filtered sample. For major cation analyses, 200 ml of water were passed through a 0.45 mL filter and 2 ml of 6N HCl were added to maintain metals in solution. In each split headspace was minimized. Samples were kept on ice and shipped for overnight delivery to the KGS laboratory in Lawrence, Kansas.

GROUND-CONDUCTIVITY MEASUREMENTS

Measurements made using a ground conductivity meter in representative environments (figs. 7 and 8; appendix A) show that apparent ground conductivities in the shallow subsurface are relatively high across the Petronila Creek area. In the horizontal dipole (HD) instrument orientation, where the measured value represents the apparent conductivity within the upper 3 m of the subsurface, conductivity ranged from 95 to 1065 millisiemens per meter (mS/m) and averaged 370 mS/m (table 2). Measurements taken along the creek and away from it depict a general trend of increasing apparent conductivity from northwest to southeast toward the coast. The lowest conductivities (188 mS/m or less) are found only in the northwest half of the study area (fig. 7). With the exception of a single high value taken in a background area along Nueces County Road 30 (location P110, appendix A), all measurements higher than 272 mS/m were located on the coastal side of U.S. 77 (fig. 7).

Measurements taken in the vertical dipole (VD) orientation, which represents apparent conductivity in the upper 6 m of the subsurface, are also high across the area (fig. 7; appendix A). These measurements average 294 mS/m, lower than the HD average. Apparent conductivity measured in the VD orientation also generally increases from northwest to southeast toward the coast (fig. 8). Lowest values (185 mS/m or less) are all located in the northwest half of the study area. The highest values (343 mS/m or greater) are all located to the southeast of U.S. 77.

At most locations (100 of 165), the shallow (HD) measurement is greater than the deeper (VD) measurement, a relationship that is also borne out by higher average HD conductivities (table 2). In potentially salinized areas such as Petronila Creek, this relationship suggests that the sources of salinity are at or near the surface and that downward infiltration is limited.

Elevated apparent conductivities measured throughout the area are likely the combined result of (a) the presence of clayey Beaumont Formation sediments at or near the surface (Brown and others, 1975); (b) generally high moisture content in area soils; and (c) relatively high soil and sediment salinities caused by original depositional salinity, salts recently deposited by prevailing winds or inundation by saline water during storms, or discharge and migration of saline water produced from area oil and gas

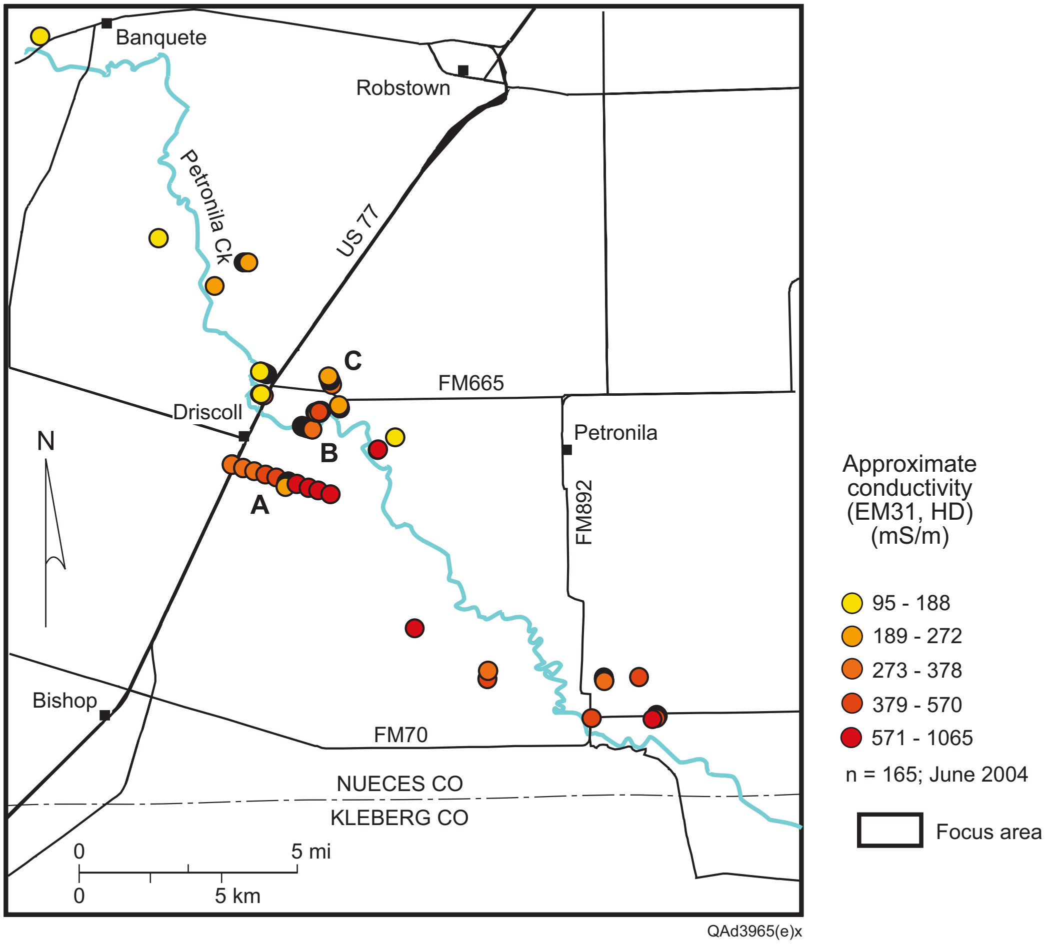

Figure 7. Apparent ground conductivity in the Petronila Creek area measured using an EM31 in the horizontal dipole (HD) mode.

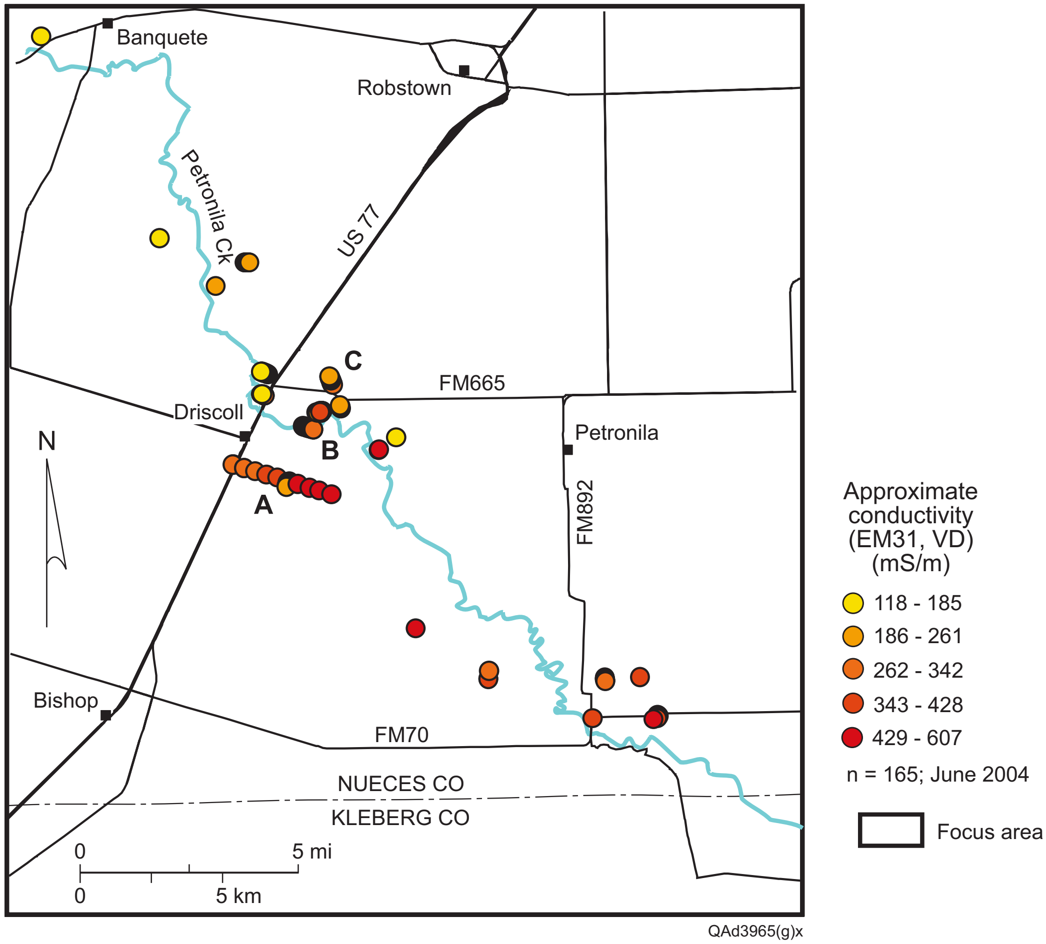

Figure 8. Apparent ground conductivity in the Petronila Creek area measured using an EM31 in the vertical dipole (VD) mode.

Table 2. Statistical parameters for apparent ground conductivity measurements acquired in June 2004 in the Petronila Creek area, Nueces and Kleberg counties, Texas (appendix A) using a Geonics EM31 instrument (fig. 5). Horizontal-dipole measurements represent the upper 3 m of the subsurface; vertical-dipole measurements represent the upper 6 m.

Instrument Orientation	Number	Average (mS/m)	Minimum (mS/m)	Maximum (mS/m)	Std. Dev. (mS/m)
Horizontal dipole	165	370	95	1065	220
Vertical dipole	165	294	118	607	294

operations. The general gulfward increase in apparent conductivity measured in both instrument orientations suggests that regional influences (syndepositional salinity sources and modern aerosol or inundation sources) control the overall trend, while oil- and gas-field sources of produced saline water might explain local increases in ground conductivity along and near Petronila Creek. More detailed descriptions of a few of the conductive areas follow.

Agua Dulce Creek to U.S. 77

The most upstream conductivity measurements were taken at Agua Dulce Creek in Sablatura Park west of Banquete (figs. 7 and 8), about 5 km upstream from the confluence with Banquete Creek and the formal upstream limit of Petronila Creek (segment 2204). Conductivity values measured along Agua Dulce Creek were the lowest in the study area (95 mS/m HD and 118 mS/m VD at location P146), reflecting low water and ground salinity in this Petronila Creek tributary. Only slightly higher measurements were recorded at Pintas Creek (179 mS/m HD and 173 mS/m VD at location P104), another Petronila Creek tributary whose confluence is about 7 km upstream from U.S. 77.

Background measurements acquired in a field along Nueces County Road 30 (CR30, figs. 7 and 8) are generally below 200 mS/m in both orientations (locations P106 to P115, appendix A), lower than similar background measurements acquired at several locations southeast of U.S. 77.

Measured apparent conductivities remain low at a small impoundment along Petronila Creek about 5 km upstream from U.S. 77 (location P105, figs. 7 and 8; appendix A), as well as along a profile approaching Petronila Creek at the Coastal Bend Youth City north of Driscoll (figs. 7 and 8), where measured conductivities are between 116 and 241 mS/m in both orientations (locations P064 to P077, appendix A).

At the U.S. 77 bridge, apparent conductivities along Petronila Creek increase from low values upstream from the bridge (150 mS/m at P063, figs. 7 and 8; appendix A) to higher values downstream from the bridge (168 to 350 mS/m in both orientations at locations P054 to P061). The general location of this increase in apparent ground conductivity coincides with the stream segment where chloride and

TDS concentrations of surface-water samples also increase (figs. 2 and 3). Generally low conductivity values measured between Agua Dulce Creek and U.S. 77 support the conclusion that there is little or no ground or surface-water salinization along Petronila Creek upstream from the Driscoll area.

Drainage Ditch Along Nueces County Road 18

The drainage ditch on the north side of Nueces County Road 18 (fig. 9) crosses the Clara Driscoll Oil Field. Highly saline water has been sampled by EA Engineering, Science, and Technology, Inc. between the oil field and the point where the ditch drains into Petronila Creek (22,000 mg/L TDS concentration at station 13032 on November 20, 2003). We measured apparent ground conductivity in the floor of the ditch at approximately 400-m intervals from U.S. 77 eastward for a distance of about 4 km (area A, figs. 7 and 8).

Apparent conductivities measured in the HD and VD orientations have similar moderate values at the upstream end of the profile (from U.S. 77 to a distance of about 1.6 km downstream, fig. 10). Along this segment and farther downstream, the deeper VD values remain near 400 mS/m. In contrast, the shallower HD values show a gradual increase from 300 mS/m near U.S. 77 (location P078, appendix A) to 470 mS/m 1.6 km downstream (location P084), followed by a steeper increase to a peak value of 1065 mS/m (location P097) about 2.8 km downstream along the ditch. The two remaining measurement locations at the downstream end of the profile (P098 and P099) show lower but still elevated values. Station 13032 is located about 400 m farther downstream from the most downstream conductivity measurement. Background conductivity values acquired in a field adjacent to County Road 18 are significantly lower than those in the ditch, ranging from 159 to 275 mS/m in both instrument orientations (location P086 to P095, appendix A).

The abrupt increase in apparent ground conductivity evident at 1.6 km from U.S. 77 suggests a local increase in ground salinity, possibly related to the spatially coincident oil field. Anomalously high HD values suggest that the salinization is restricted to the shallow zone and that downward migration is inhibited by the clay-rich Beaumont Formation substrate.

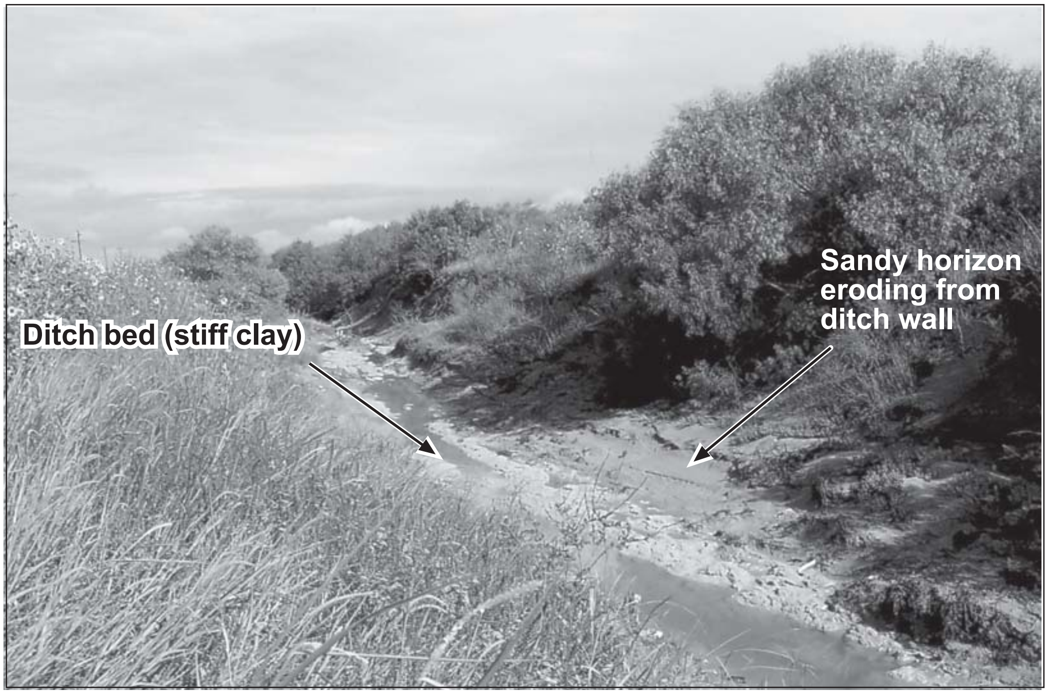

Figure 9. Drainage ditch along Nueces County Road 18 near Driscoll. A relatively sandy horizon is eroding from the ditch wall above stiff clay that forms the bed of the ditch. Both units are within the Pleistocene Beaumont Formation.

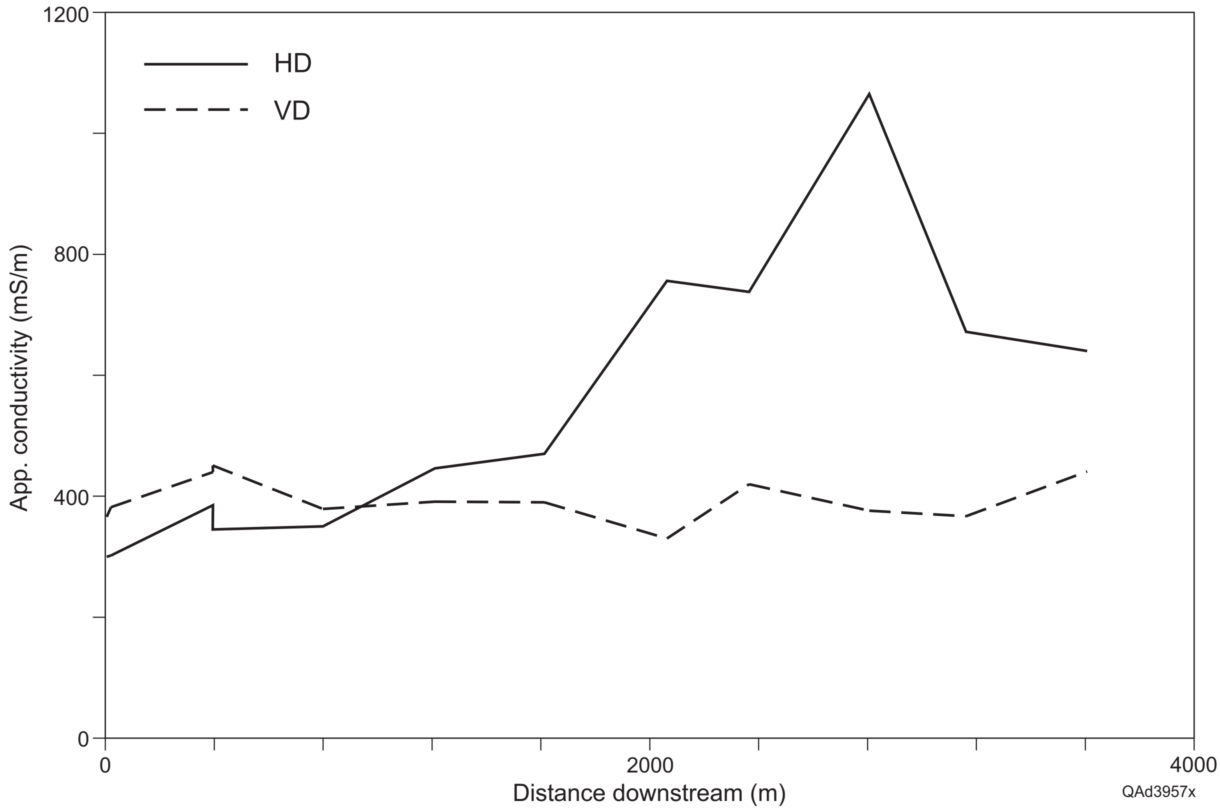

Figure 10. Apparent ground conductivity profile from west to east along the drainage ditch adjacent to County Road 18 south of Driscoll.

Petronila Creek Seep Area

Petronila Creek bisects the Clara Driscoll and North Clara Driscoll oil fields about 3 km northeast of Driscoll (fig. 4). We acquired ground conductivity data within the northern part of the Clara Driscoll Oil Field (area B, figs. 7 and 8) in several representative settings: across a cultivated field away from the creek, atop the south bluff adjacent to the creek, across an abandoned well site barren of vegetation, and along a short segment of the creek bed. At the time the measurements were made along the creek bed, saline water saturated the stream bank and a slight oil sheen was visible on standing water at the creek bottom (fig. 11).

Measured apparent conductivity was in the moderate to low category in the presumed background area across a cultivated field northeast of Driscoll (locations P002 to P019, appendix A; area B, figs. 7 and 8). Measured values ranged from 195 to 247 mS/m in both orientations.

Similar low to moderate conductivities were measured in cultivated fields atop the south bluff of Petronila Creek in area B. Values along an upstream segment ranged from 195 to 290 mS/m (locations P025 to P030, appendix A). Similar values (182 to 269 mS/m) were measured in a similar setting farther downstream in area B (locations P047 to P053, appendix A).

In contrast to the low to moderate conductivities measured on the upland, conductivities measured in the inferred seep area along Petronila Creek (locations P031 to P038, appendix A) exceed 600 mS/m in the HD orientation and 300 mS/m in the VD orientation (fig. 12). Elevated conductivities were also measured across an abandoned oil field site on the bluff above the inferred seep area (232 to 891 mS/m at locations P039 to P046, appendix A). High measured conductivities at these sites suggest local salinization of the shallow subsurface that is likely to be related to oil-field activities. Higher apparent conductivities measured in the shallower HD orientation suggest limited downward infiltration of saline water into clayey Beaumont Formation strata.

Figure 11. Photograph of apparent salt-water and hydrocarbon seep area along Petronila Creek northeast of Driscoll.

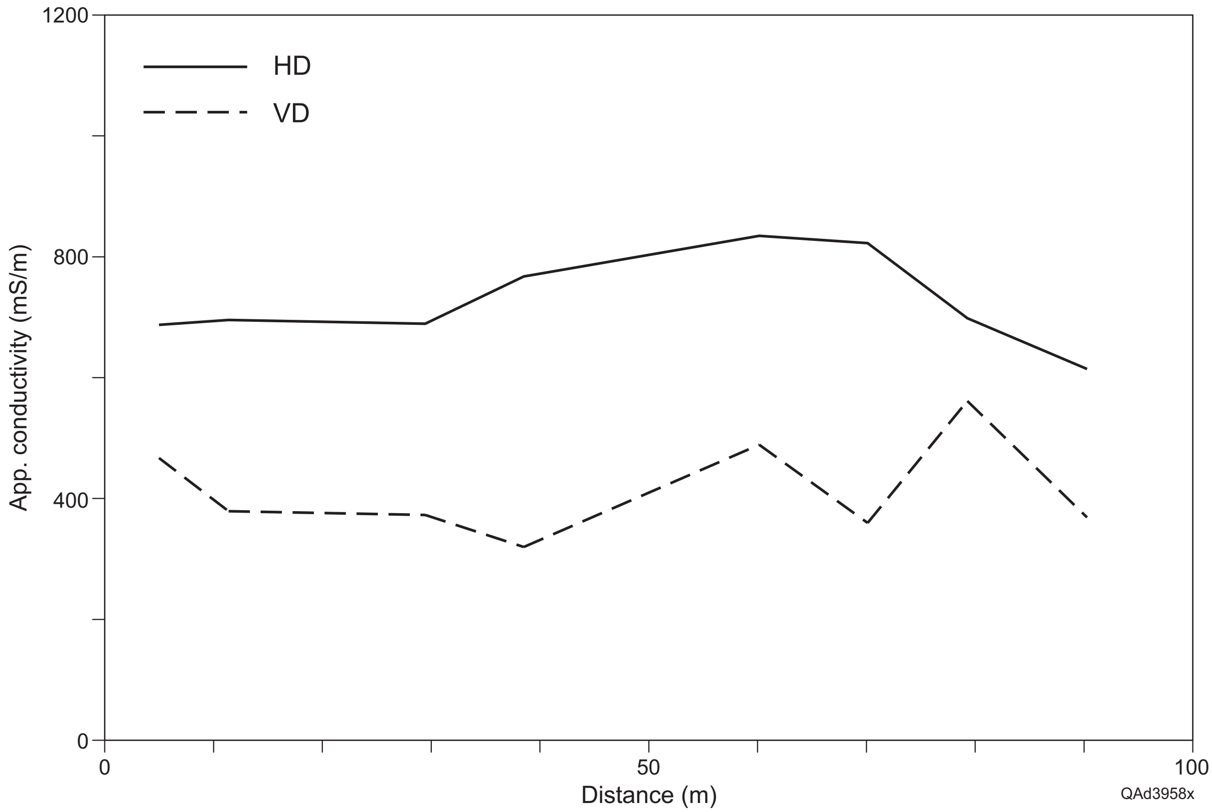

Figure 12. Apparent ground conductivity profile in the seep area along Petronila Creek.

Former Pit, North Clara Driscoll Oil Field

A barren area about 150 m across is located in a cultivated field in the North Clara Driscoll Oil Field about 500 m north of Petronila Creek (area C, figs. 7 and 13). According to the Railroad Commission of Texas, this is the site of a former saltwater separation pond (F. Munoz, pers. comm., 2004) that has been abandoned and filled. Multiple shallow monitoring wells have been installed in the barren area and in the surrounding cultivated field (fig. 13). We acquired apparent conductivity measurements along a profile line that crossed the barren area approximately north–south and extended beyond the barren area into the cultivated field to the north and south (fig. 14; locations P147 to 178, appendix A).

Apparent conductivities are higher across the barren area in both instrument orientations. In the shallower HD mode, apparent conductivities exceed 400 mS/m across the entire barren area and reach a peak value of 963 mS/m near the center of the barren area (fig. 14). Outside of the barren area, apparent conductivity remains higher to the south (downslope toward Petronila Creek) than it does to the north in both the shallower HD and deeper VD orientations. The HD measurements reach likely background values of less than 275 mS/m north of the barren area. Elsewhere along the profile, HD values are higher than VD values, suggesting shallow salinity sources with limited downward infiltration.

AIRBORNE SURVEY RESULTS

Previous studies and reconnaissance ground-based investigations confirmed the presence of significant ground and stream salinization and defined its geographic extent. The affected area (fig. 4) was large enough to justify the use of an airborne EM instrument to rapidly measure ground conductivities at multiple exploration depths to better characterize salinization.

Exploration Depth

The exploration depth of the airborne EM instrument is governed by instrument frequency and ground conductivity. The GEM-2A instrument used in our airborne survey operated at five primary

Figure 13. Photograph of barren area and monitor wells in the North Clara Driscoll Oil Field.

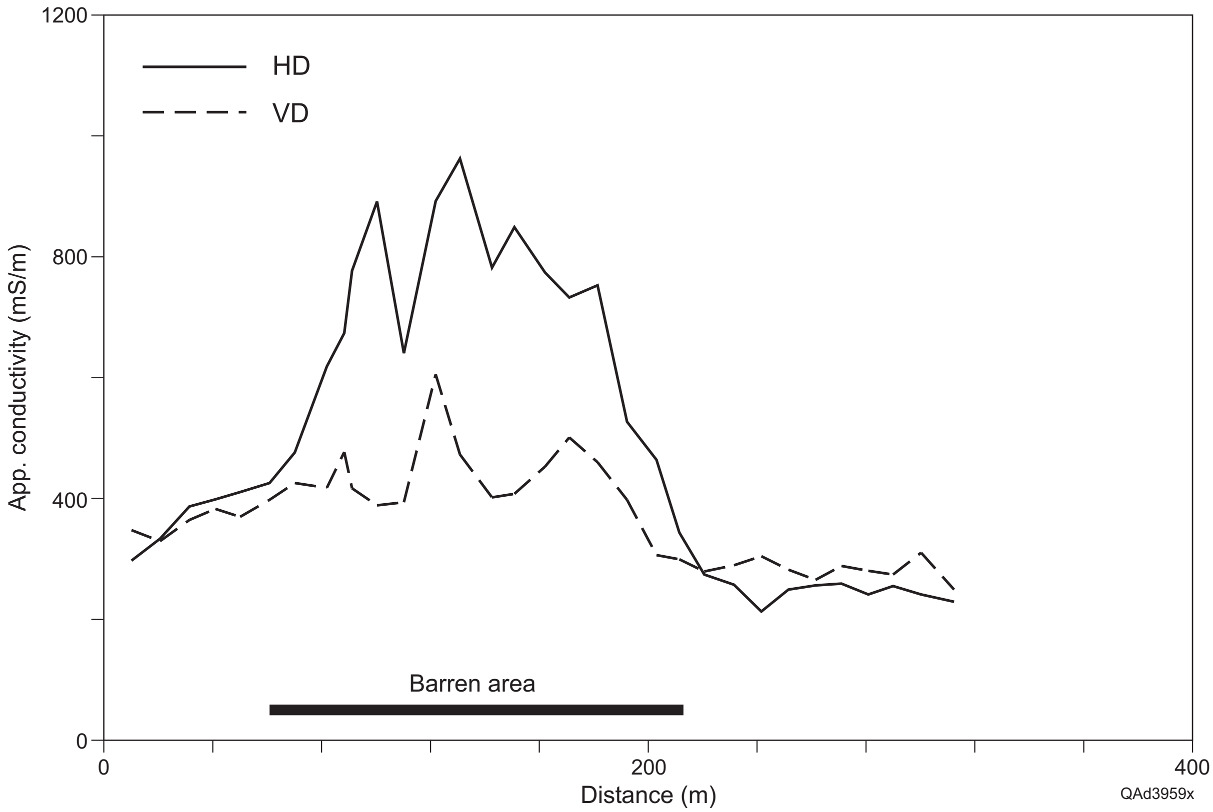

Figure 14. Apparent ground conductivity profile from south to north across the barren area in the North Clara Driscoll Oil Field.

(transmitter) frequencies that ranged from 450 Hz to 39,030 Hz (table 1). Because the exploration depth of these instruments decreases as either frequency or ground conductivity increases, coils operating at different primary frequencies will measure different apparent conductivities over ground where the actual conductivity varies with depth. Exploration depth is approximated by "skin" depth, which is defined as the depth at which the field strength generated by the transmitter coil is reduced to 1/e times its original value. Skin depth is calculated using the equation

$$d = k\,(r / f\,)^{0.5}$$

where d = skin depth (in m), k = 500 (m/ohm-s)$^{0.5}$, r = resistivity (in ohm-m), and f = EM frequency (in cycles/s) (Telford and others, 1990). Recast into equivalent, reciprocal conductivity terms, this equation becomes

$$d = k\,(1 / \sigma f\,)^{0.5}$$

where k = 15,681 (m-mS/s)$^{0.5}$, σ = conductivity (in mS/m), and f = EM frequency.

We used apparent conductivity measurements made in the survey area with a ground-based instrument (table 1; appendix A) to estimate the exploration depths reached by the airborne instrument. Estimated exploration depth (fig. 15) over the most conductive ground (607 mS/m) is the shallowest, increasing from as much as 3 m at the highest frequency (39,030 Hz) to 30 m at the lowest frequency (450 Hz). Exploration depths are greatest over the most poorly conductive ground (95 mS/m), ranging from about 8 m at 39,030 Hz to 77 m at 450 Hz. Increasing conductivities with depth, weak induced ground currents, and cultural noise can all combine to reduce the actual exploration depth achieved in a survey. We can produce a reasonable exploration depth estimate for the area and instrument by using the average measured ground conductivity (370 mS/m in the VD orientation), which yields maximum exploration depths of 4 m at 39,030 Hz, 7 m at 12,810 Hz, 13 m at 4170 Hz, 23 m at 1350 Hz, and 39 m at 450 Hz.

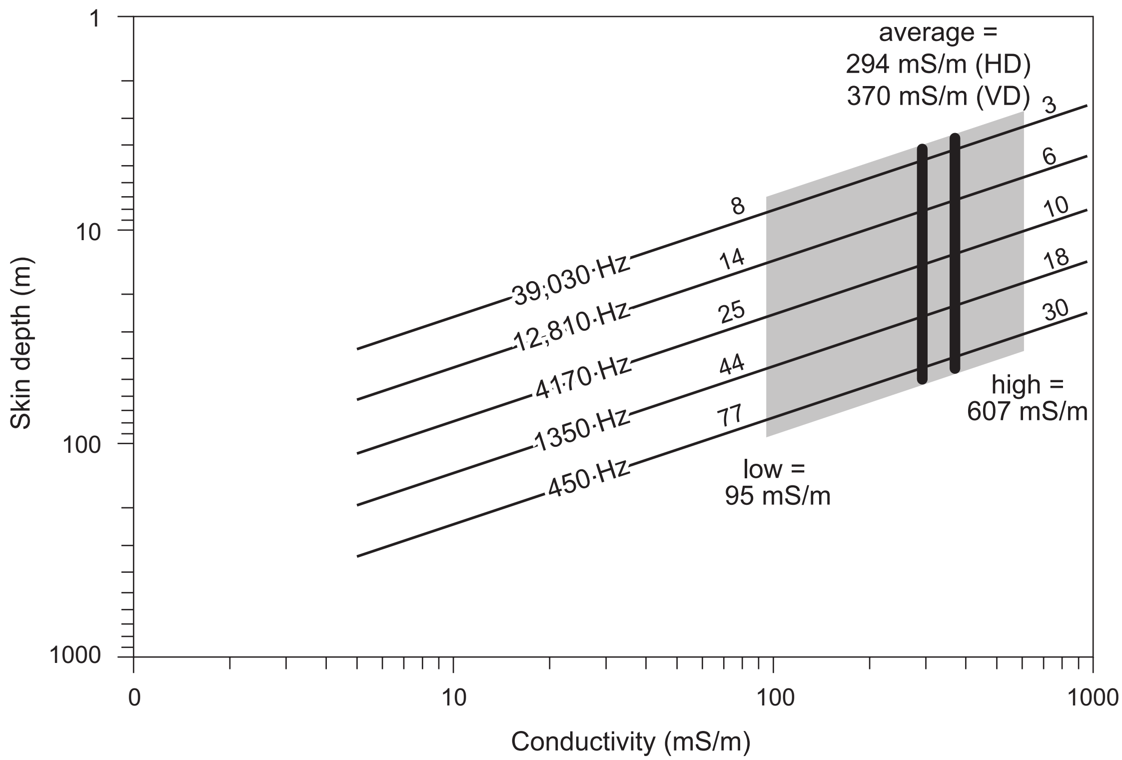

Figure 15. Approximate exploration (skin) depths for the five frequencies used in the Petronila Creek airborne EM survey. The shaded area represents the range of apparent conductivity values measured using a ground-based instrument (table 2). The heavy vertical lines are the average conductivity values measured in HD and VD orientation. The actual apparent conductivities calculated from airborne-instrument data represent a bulk value that is influenced by electrical properties of the ground between the ground surface and the exploration depth for that frequency.

Stream-Axis EM Data

Two types of airborne EM data were acquired in the Petronila Creek survey. Results from the single flight line that followed the axis of Petronila Creek can be used to identify high ground-conductivity areas caused by ground salinization along the creek. Measurements from the block survey can be used to produce apparent conductivity maps that depict the lateral extent of salinization and aid in identifying possible sources and migration routes to the creek.

Stream-axis data consist of apparent conductivity measurements for five frequencies at 12,919 locations along the 38-km-long segment of Petronila Creek, resulting in a sample spacing of about 3 m (figs. 16 to 20). Average conductivities were high, ranging from 553 to 1304 mS/m for all frequencies (table 3). Similar to the ground-based measurements, conductivities were highest for the higher, shallow-exploring frequencies.

Relatively low stream-axis conductivities were measured at all frequencies upstream from U.S. 77 (figs. 16 to 20). Farther downstream, apparent conductivity trends differ according to location and frequency. At the deepest-exploring frequency, significant conductivity highs are located between FM 665 and FM 892 and downstream from FM 70 (fig. 16). High values extend to other deep- and intermediate-exploring frequencies (1350 and 4170 Hz), particularly downstream from FM 70 (figs. 17 and 18). The shallowest-exploring frequencies (12,810 and 39,030 Hz) recorded the highest conductivities farther upstream between FM 665 and FM 892 (figs. 19 and 20).

Petronila Creek Block EM Data

Ground conductivity measurements were made at all frequencies at 214,081 points within the Petronila Creek block and were gridded to produce apparent conductivity maps at each frequency (figs. 21 to 25). Average conductivities over the block ranged from 378 to 1477 mS/m for all frequencies, similar to the values along the creek axis (table 3). Highest apparent conductivities were measured at the highest (shallowest-exploring) frequency.

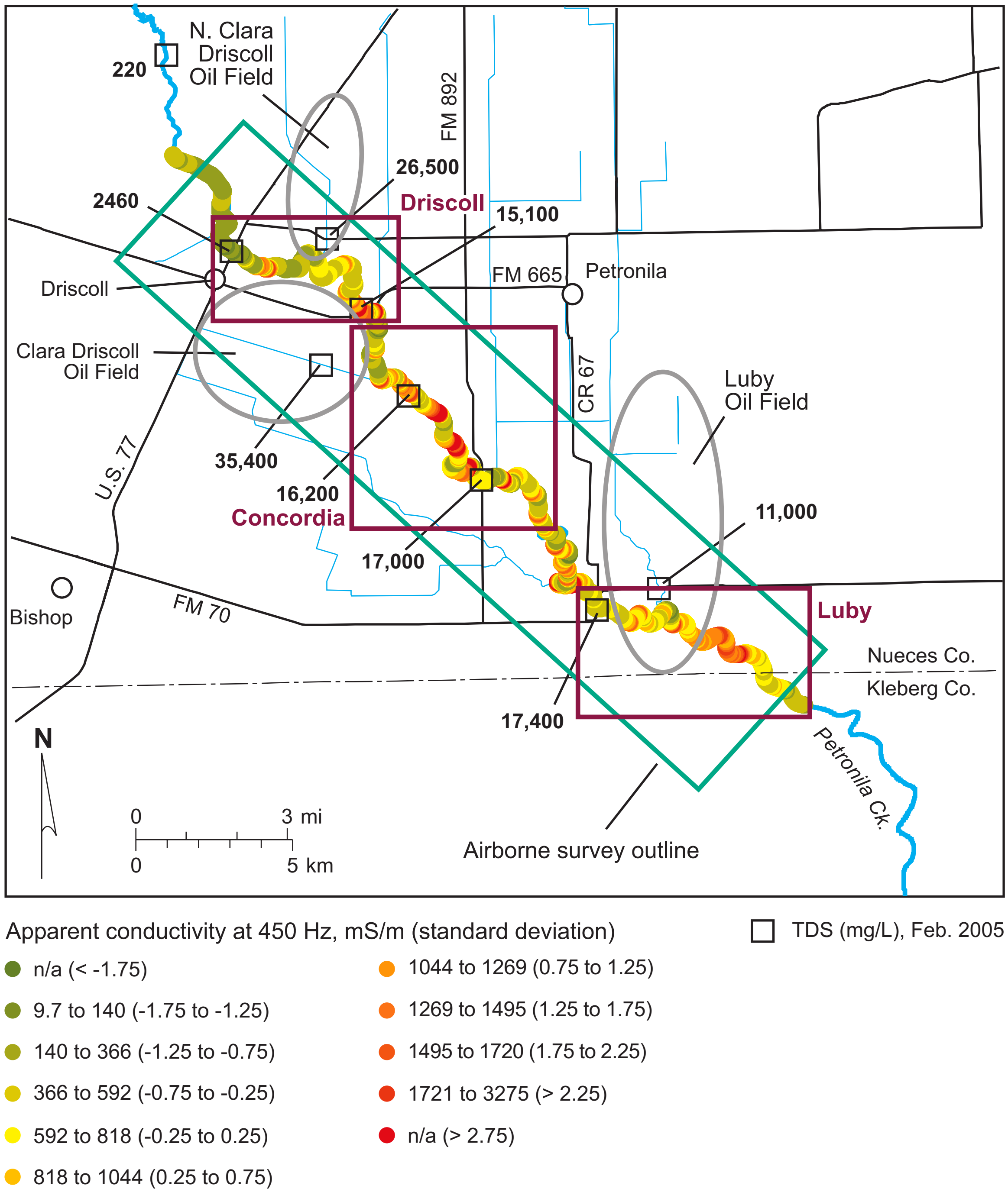

Figure 16. Apparent conductivity measured at 450 Hz during the airborne survey along the axis of Petronila Creek (colored dots). Also shown are the Driscoll, Concordia, and Luby high-conductivity areas (red rectangles) and Petronila Creek and tributary TDS concentrations measured in February 2005 at the time of the airborne survey (black squares). The 450-Hz frequency explores from the land surface to an average depth of about 28 m, estimated from the average apparent conductivity measured at this frequency along the creek axis.

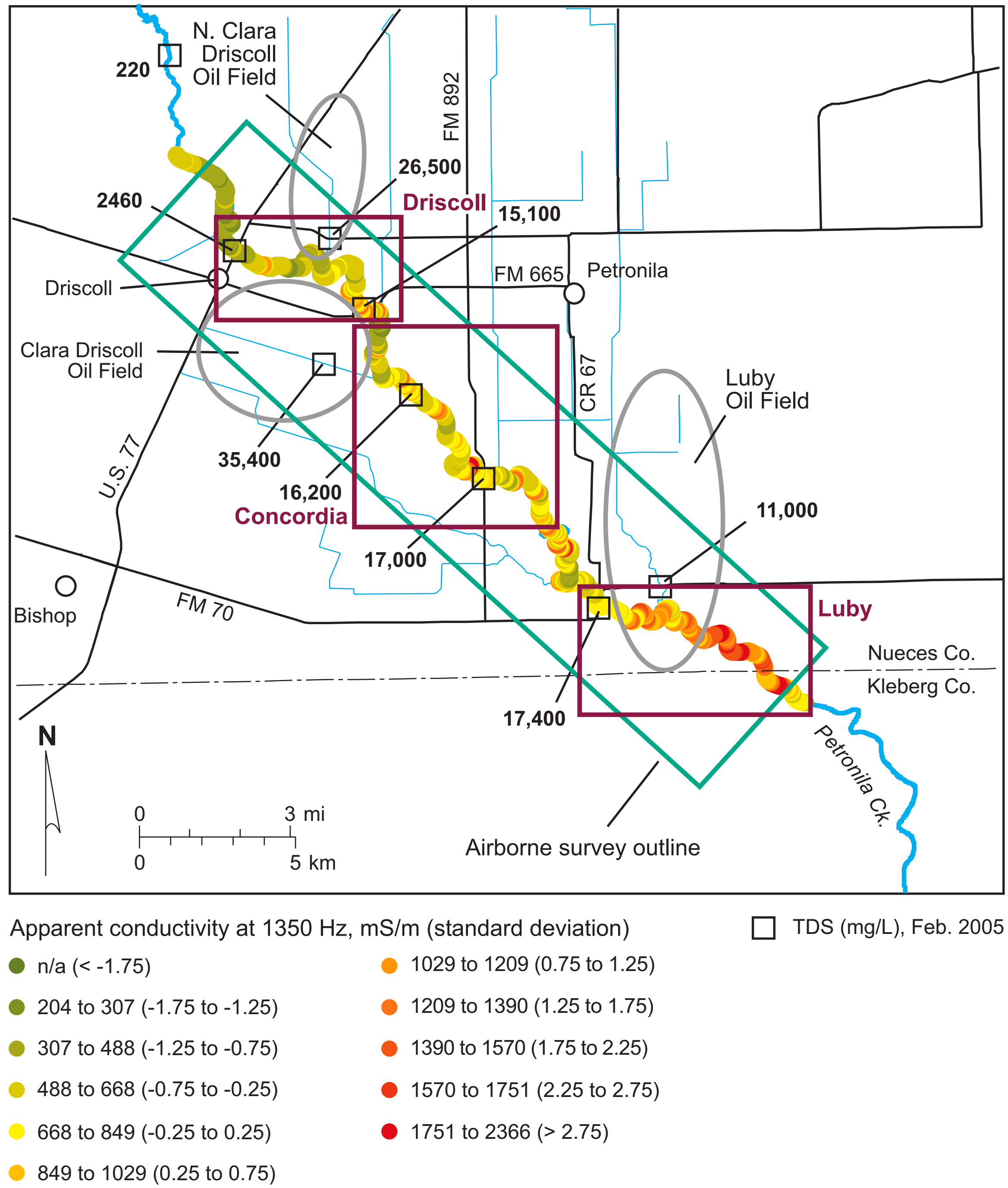

Figure 17. Apparent conductivity measured at 1350 Hz along the axis of Petronila Creek (colored dots). Also shown are the Driscoll, Concordia, and Luby high-conductivity areas (red rectangles) and Petronila Creek and tributary TDS concentrations measured in February 2005 at the time of the airborne survey (black squares). The 1350-Hz frequency explores from the land surface to an average depth of about 16 m.

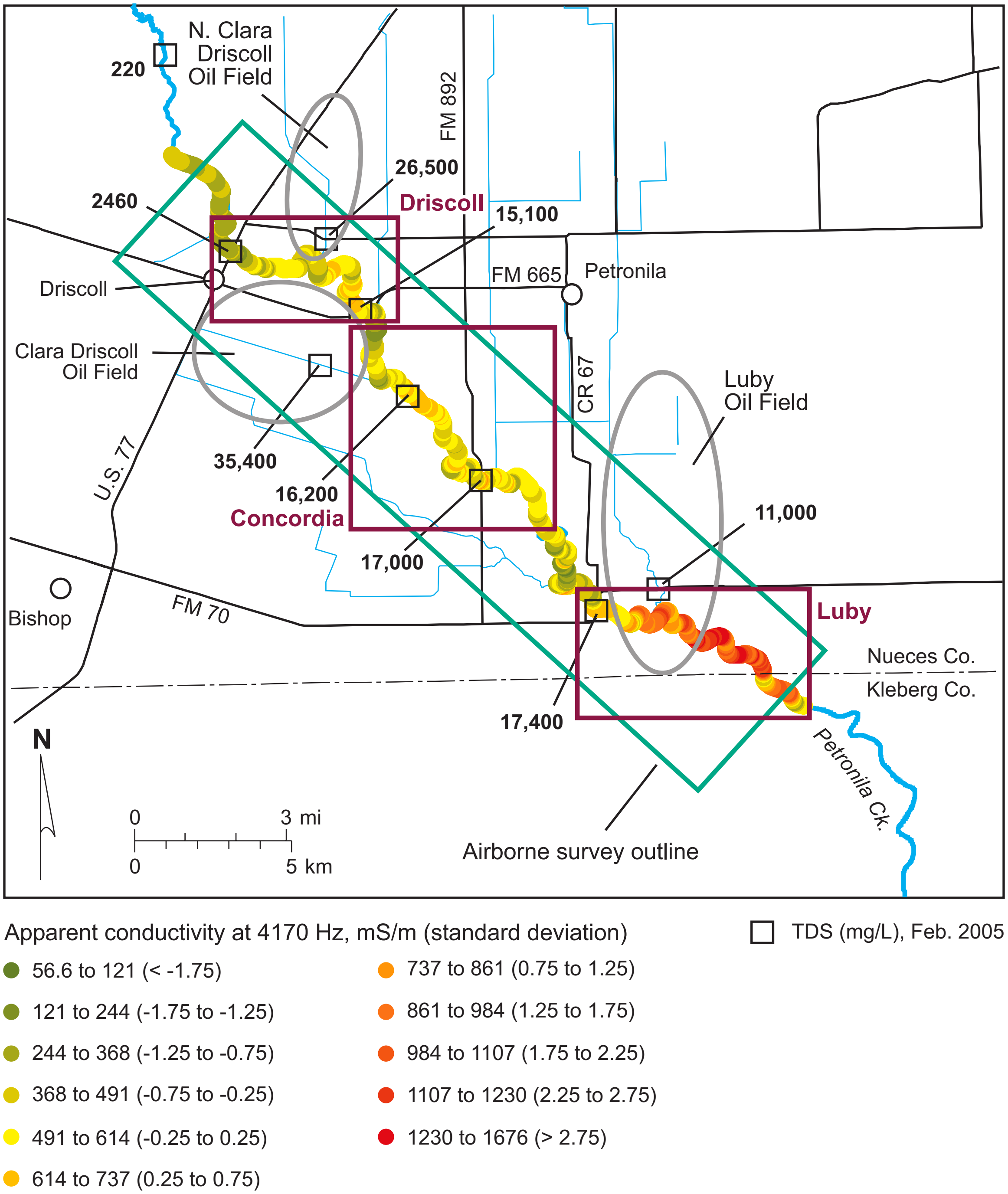

Figure 18. Apparent conductivity measured at 4170 Hz along the axis of Petronila Creek (colored dots). Also shown are the Driscoll, Concordia, and Luby high-conductivity areas (red rectangles) and Petronila Creek and tributary TDS concentrations measured in February 2005 at the time of the airborne survey (black squares). The 4170-Hz frequency explores from the land surface to an average depth of about 10 m.

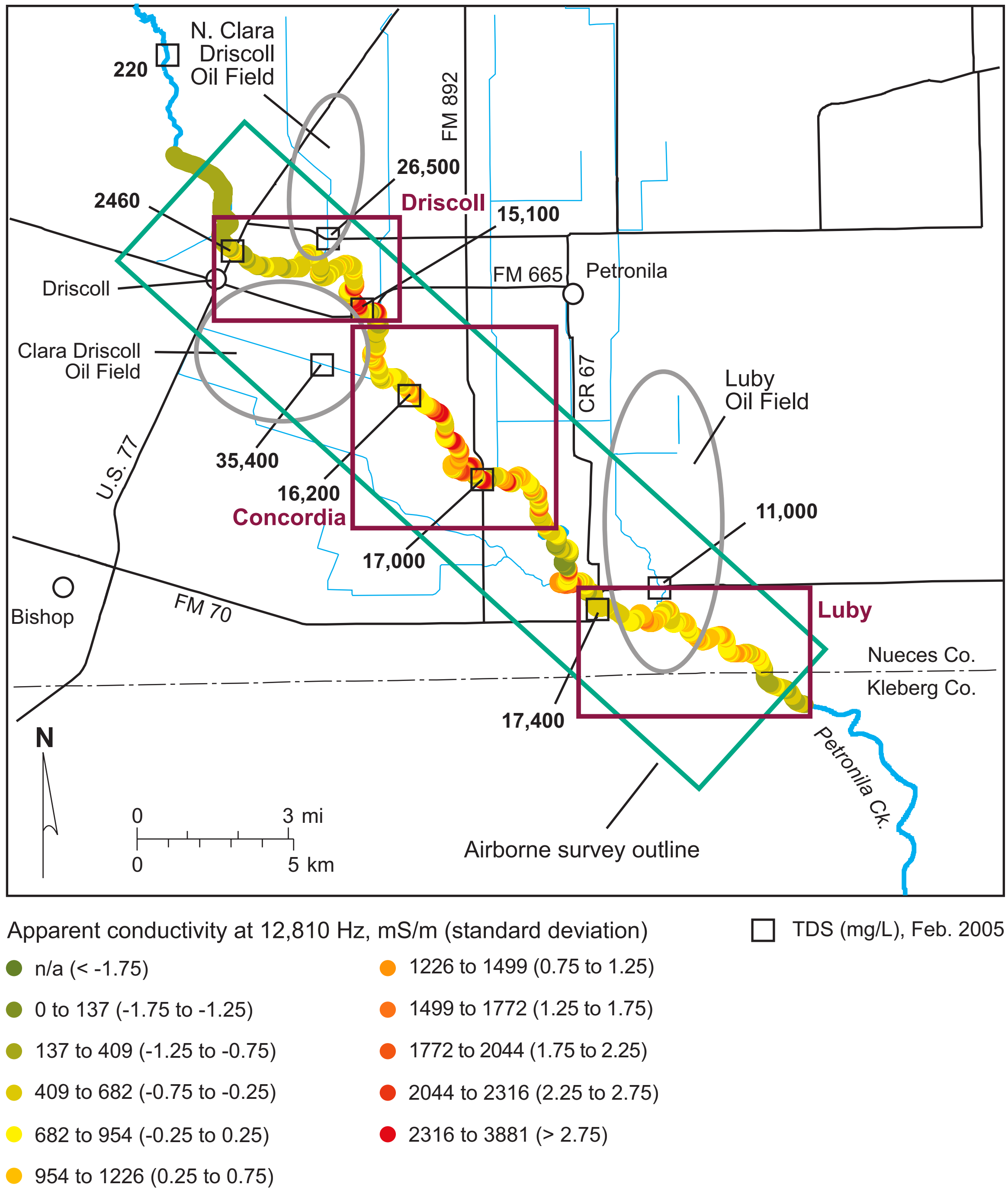

Figure 19. Apparent conductivity measured at 12,810 Hz along the axis of Petronila Creek (colored dots). Also shown are the Driscoll, Concordia, and Luby high-conductivity areas (red rectangles) and Petronila Creek and tributary TDS concentrations measured in February 2005 at the time of the airborne survey (black squares). The 12,810-Hz frequency explores from the land surface to an average depth of about 5 m.

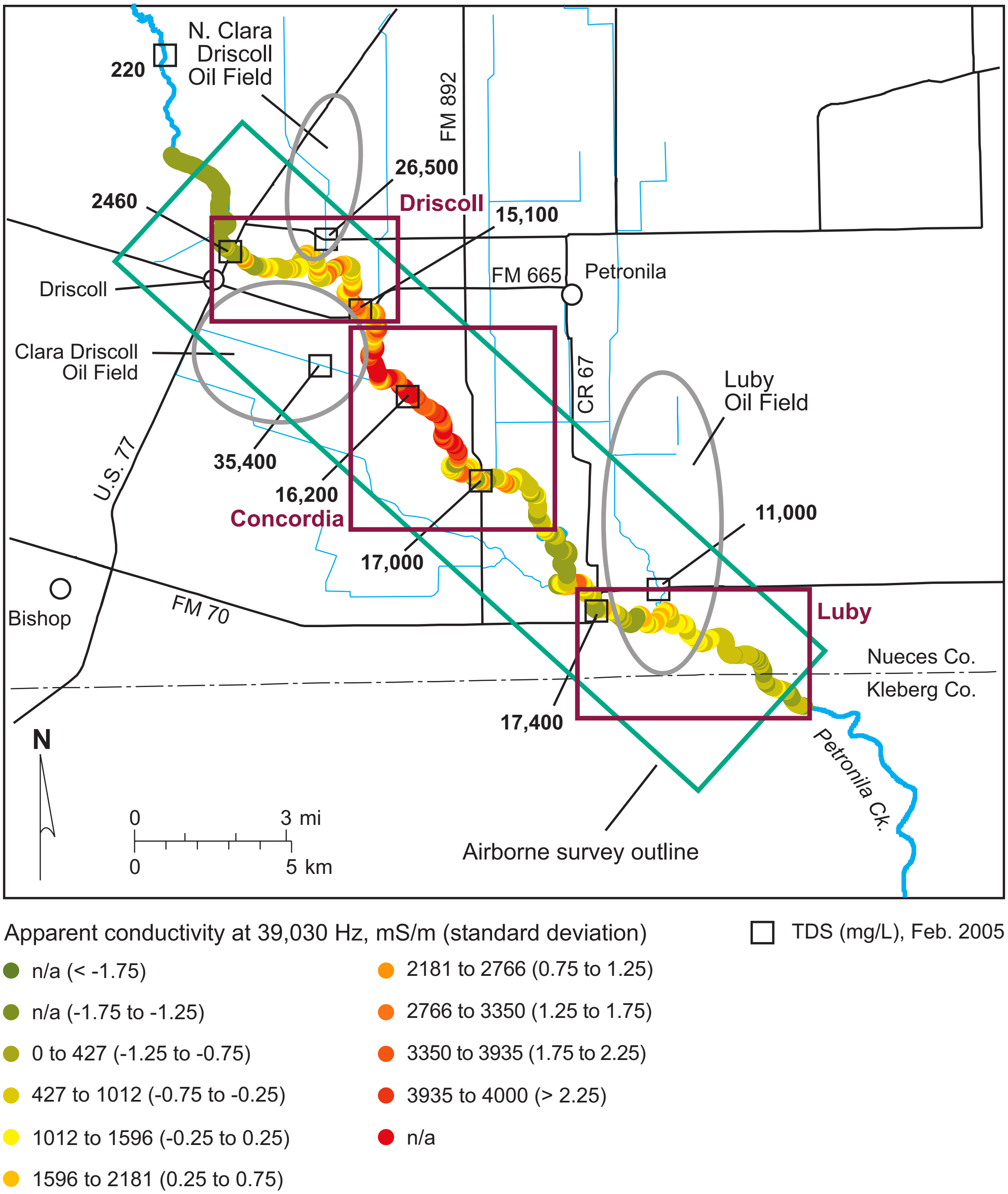

Figure 20. Apparent conductivity measured at 39,030 Hz along the axis of Petronila Creek (colored dots). Also shown are the Driscoll, Concordia, and Luby high-conductivity areas (red rectangles) and Petronila Creek and tributary TDS concentrations measured in February 2005 at the time of the airborne survey (black squares). The 39,030-Hz frequency explores from the land surface to an average depth of about 2 m.

Table 3. Average apparent conductivities measured at each frequency during the airborne geophysical survey of Petronila Creek.

	EM frequency (Hz)				
Segment	**450**	**1350**	**4170**	**12,810**	**39,030**
Petronila Creek axis	704	758	553	818	1304
“Background” above U.S. 77	290	403	342	282	181
Driscoll area	573	581	458	720	1294
Concordia area	823	726	495	1114	2265
Luby area	771	1092	850	769	807
Petronila Creek block	574	721	597	378	1477

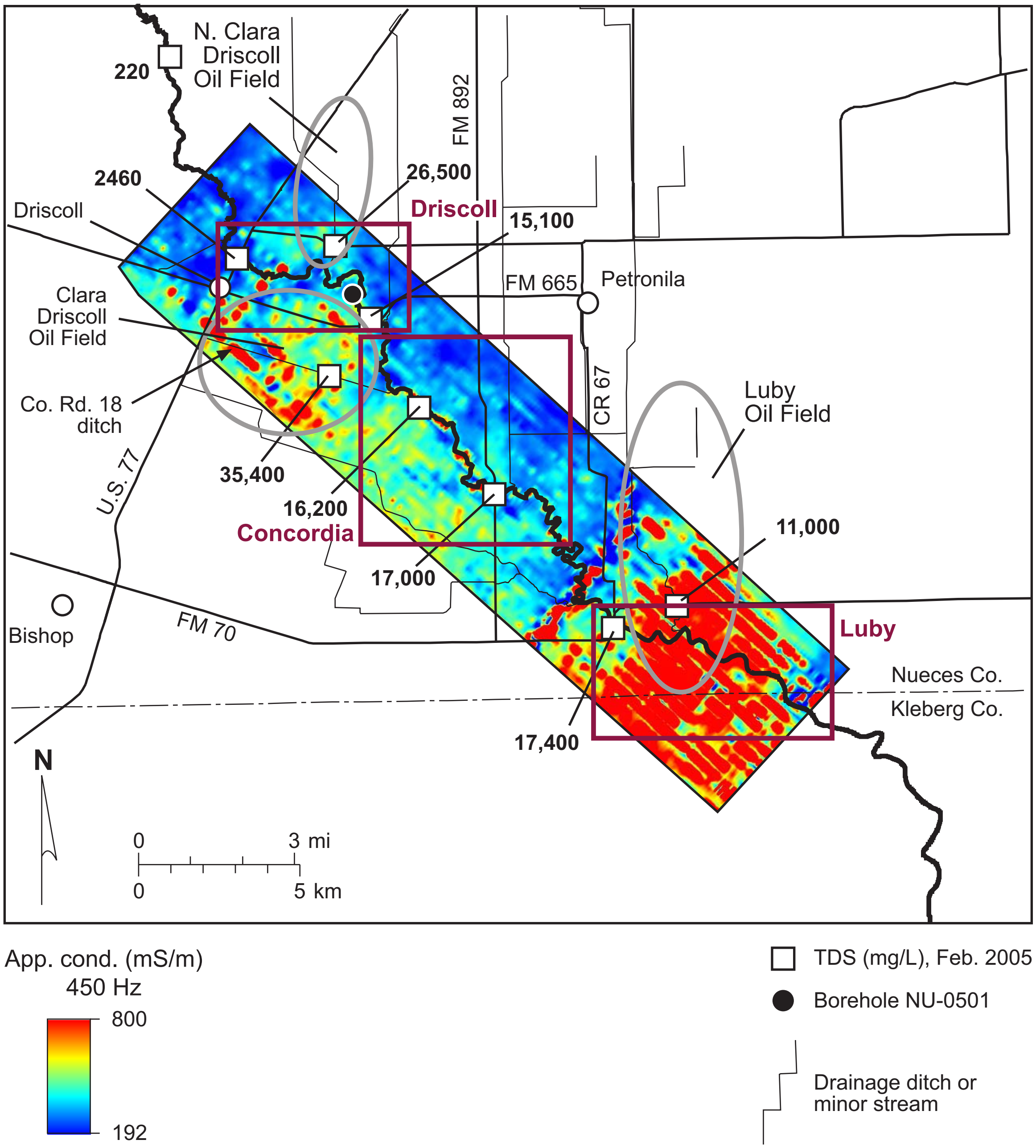

Figure 21. Apparent conductivity measured at 450 Hz during the airborne survey of the Petronila Creek block. Also shown are the Driscoll, Concordia, and Luby high-conductivity areas (red rectangles) and Petronila Creek and tributary TDS concentrations measured by EA in February 2005 one to two days after the airborne survey was completed. The 450-Hz frequency explores from the land surface to an average depth of about 28 m, estimated from the average apparent conductivity measured at this frequency along the creek axis.

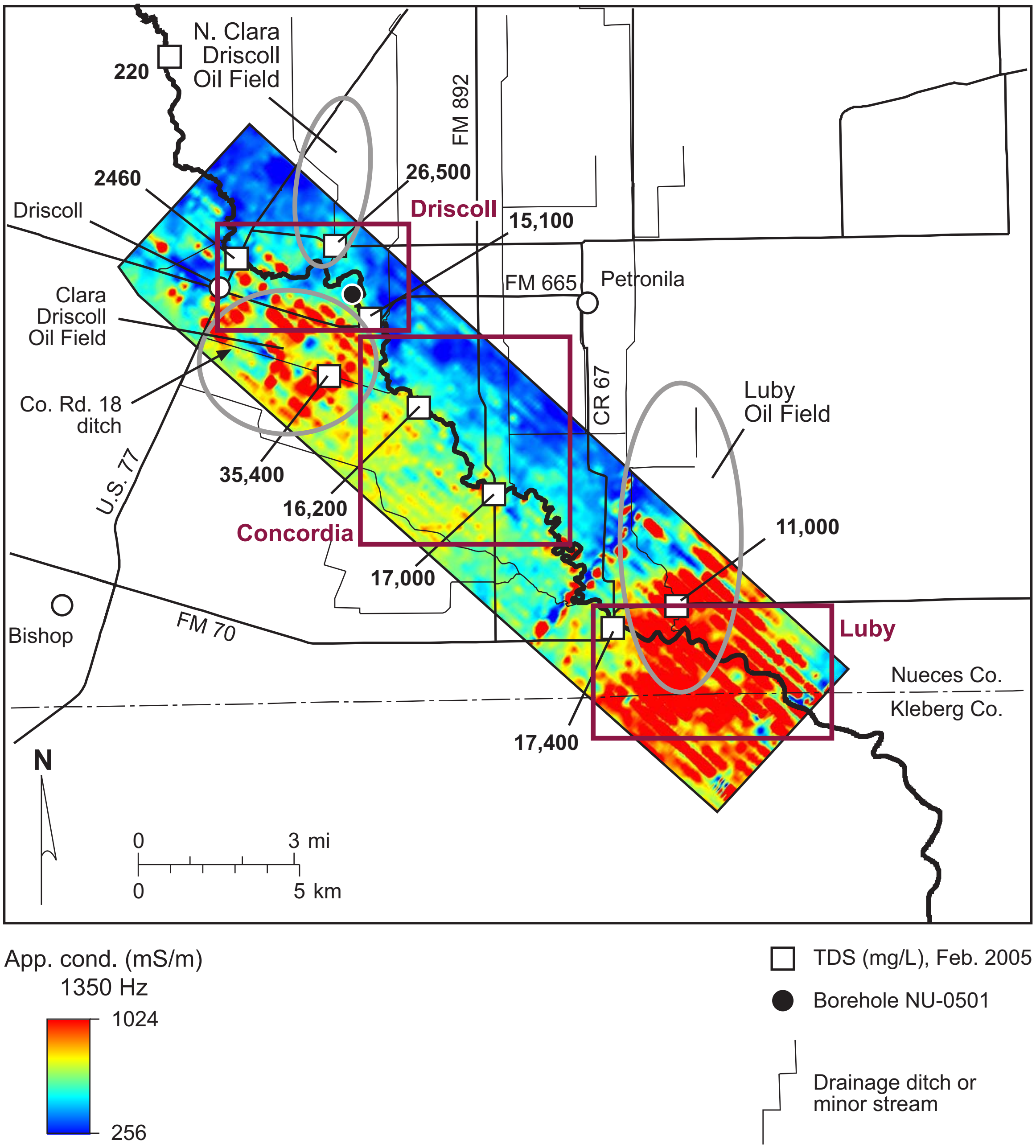

Figure 22. Apparent conductivity measured at 1350 Hz in the Petronila Creek block. The 1350-Hz frequency explores from the land surface to an average depth of about 16 m.

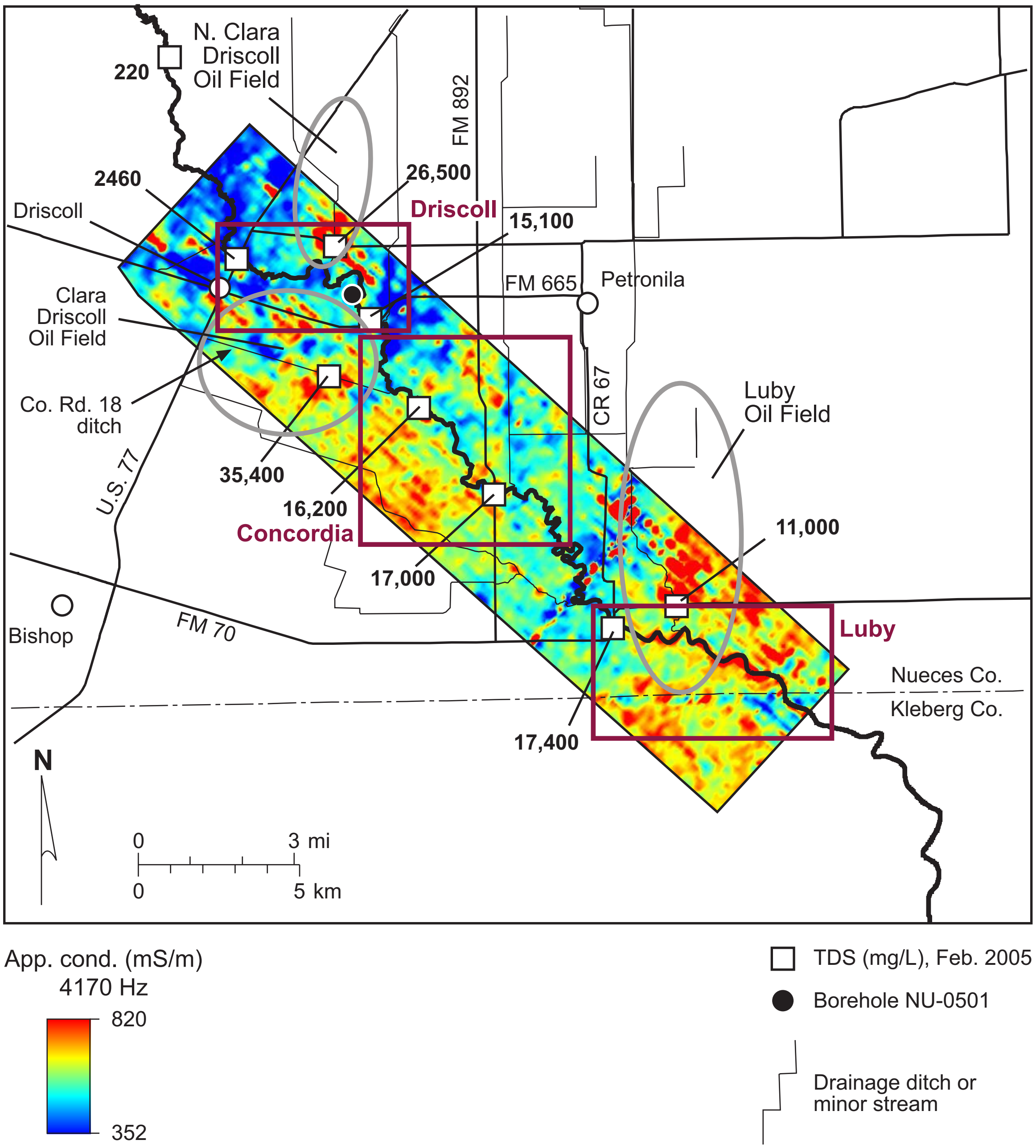

Figure 23. Apparent conductivity measured at 4170 Hz in the Petronila Creek block. The 4170-Hz frequency explores from the land surface to an average depth of about 10 m.

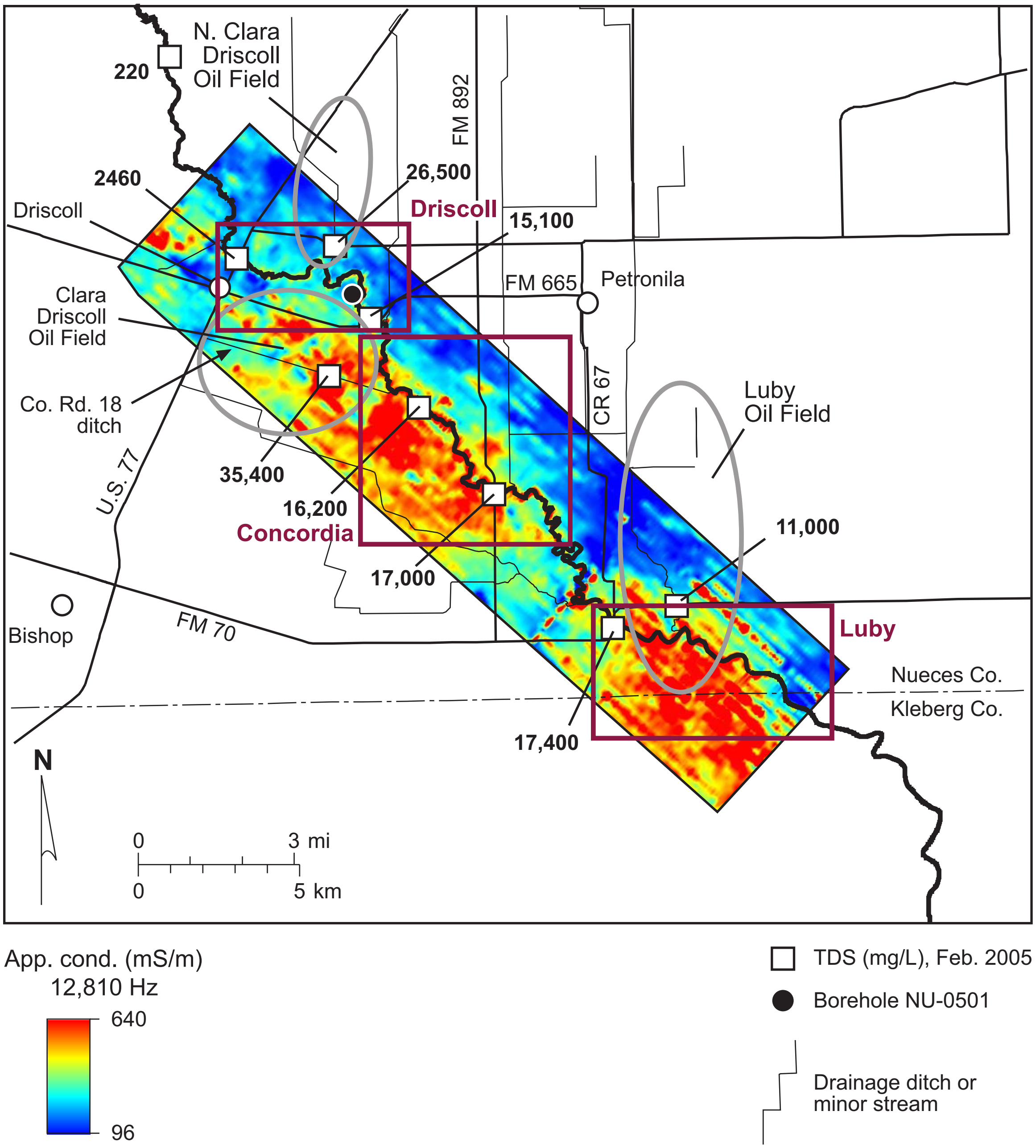

Figure 24. Apparent conductivity measured at 12,810 Hz in the Petronila Creek block. The 12,810-Hz frequency explores from the land surface to an average depth of about 5 m.

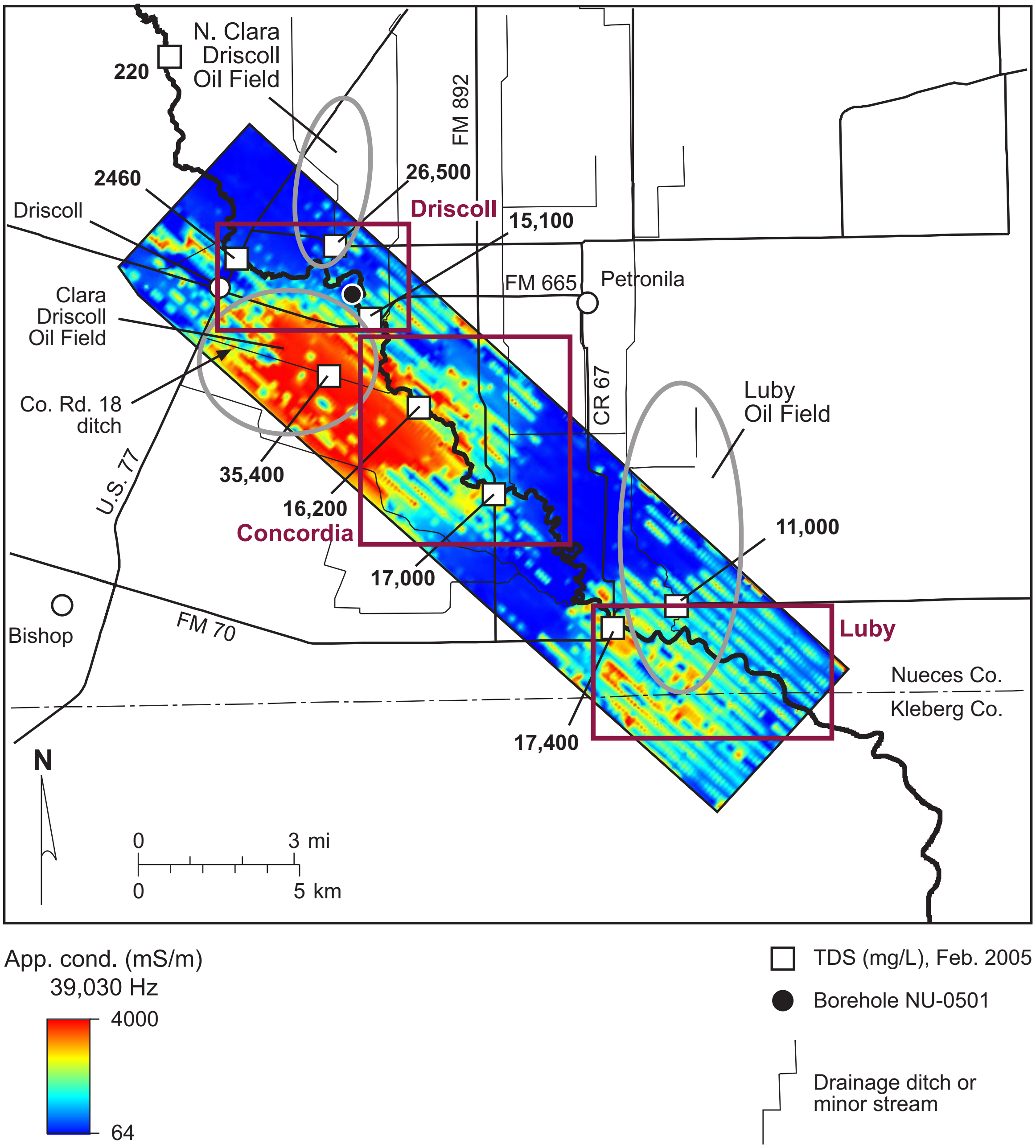

Figure 25. Apparent conductivity measured at 39,030 Hz in the Petronila Creek block. The 39,030-Hz frequency explores from the land surface to an average depth of about 2 m.

General conductivity trends in the Petronila Creek block are similar to those evident in the stream-axis data. Apparent conductivities are low at all frequencies near Petronila Creek upstream from U.S. 77 (figs. 21 to 25). Similarly, at all but the highest (shallowest-exploring) frequency, high conductivities are measured over a broad area extending downstream from FM 70 in southern Nueces and northern Kleberg counties. This is particularly well expressed at the two lowest (deepest-exploring) frequencies (figs. 21 and 22). This area includes part of the Luby Oil Field.

Upstream from FM 70, apparent conductivities at all frequencies are higher south of Petronila Creek than they are north of the creek. A broad zone of generally high conductivity is evident south of the creek that extends from the Driscoll area southeastward to near FM 892 at all frequencies. This area includes the Clara Driscoll Oil Field and all or part of two major drainage ditches that cross the oil field. Less extensive high-conductivity areas are found north of Petronila Creek at the south end of the North Clara Driscoll Oil Field on the intermediate-frequency map (fig. 23) and along the creek between FM 665 and FM 892 on the intermediate- to high-frequency maps (figs. 24 and 25).

HIGH-CONDUCTIVITY AREAS

Apparent conductivity trends evident in block and stream-axis EM data at all frequencies allow delineation of three areas of generally elevated apparent ground conductivity along the creek. From upstream to downstream, these include (1) the Driscoll area extending a total creek length of about 7.7 km downstream from the U.S. 77 bridge to the FM 665 bridge; (2) the Concordia area extending a total creek length of about 9 km from about 1 km below the FM 665 bridge to about 2 km below the FM 892 bridge; and (3) the Luby area extending from the FM 70 bridge to near the end of the survey about 8.5 km farther downstream. They represent the creek segments most likely to be contributing highly saline water that degrades Petronila Creek water quality.

The lowest conductivities measured in the airborne EM survey are found upstream from U.S. 77 (figs. 16 to 25). Average conductivities in this background, relatively nonsalinized area range from 181 to 403 mS/m and represent the lowest average conductivity at each frequency (table 3). In further contrast to the high-conductivity areas downstream, the lowest conductivities in the background area were measured at the highest (shallowest-exploring) frequencies.

Driscoll Area

The most upstream of the high-conductivity creek segments is in the Driscoll area, extending 7.7 km from U.S. 77 to FM 665. The creek passes between the Clara Driscoll and North Clara Driscoll oil fields. Two drainage ditches enter Petronila Creek from the north (fig. 16). The more upstream of the two ditches drains an area that includes the North Clara Driscoll Oil Field.

Average conductivities in the stream-axis data show the greatest increase over background values at the two highest frequencies, increasing from 282 to 720 mS/m at 12,810 Hz and 181 to 1294 mS/m at 39,030 Hz (table 3). Smaller increases were measured at lower frequencies. Stream-axis conductivities depicted on maps (figs. 16 to 20) and on a pseudosection along the creek constructed from all frequencies (fig. 26) confirm that near-surface ground conductivity increases downstream. Elevated high-frequency (near-surface) conductivities begin just downstream from U.S. 77 and become more laterally extensive downstream between the drainage ditches (4 to 9 km, fig. 26). EM data from the block survey depict high apparent conductivities south of the creek at all frequencies (figs. 21 to 25). These high conductivities are located within and southeast of the Clara Driscoll Oil Field, extending far enough south to intersect the drainage ditch along County Road 18 (figs. 21 to 25).

Elevated apparent conductivities at the shallowest-exploring frequencies are consistent with near-surface salinization along the Driscoll segment of Petronila Creek that increases in extent and intensity downstream. Shallow ground salinization along this segment coincides with an increase in TDS concentration in Petronila Creek water measured by EA in February 2005 at the time of the airborne survey (fig. 16). Their measurements showed that TDS concentration increased from 2460 mg/L at U.S. 77 (station 13098) at the upstream end of the segment to 15,100 mg/L at FM 665 (station 13098) near the downstream end of the segment. A comparison of chemical analyses of surface-water samples (appendix B) acquired at the time of the survey upstream from the Driscoll segment (station 13099 at

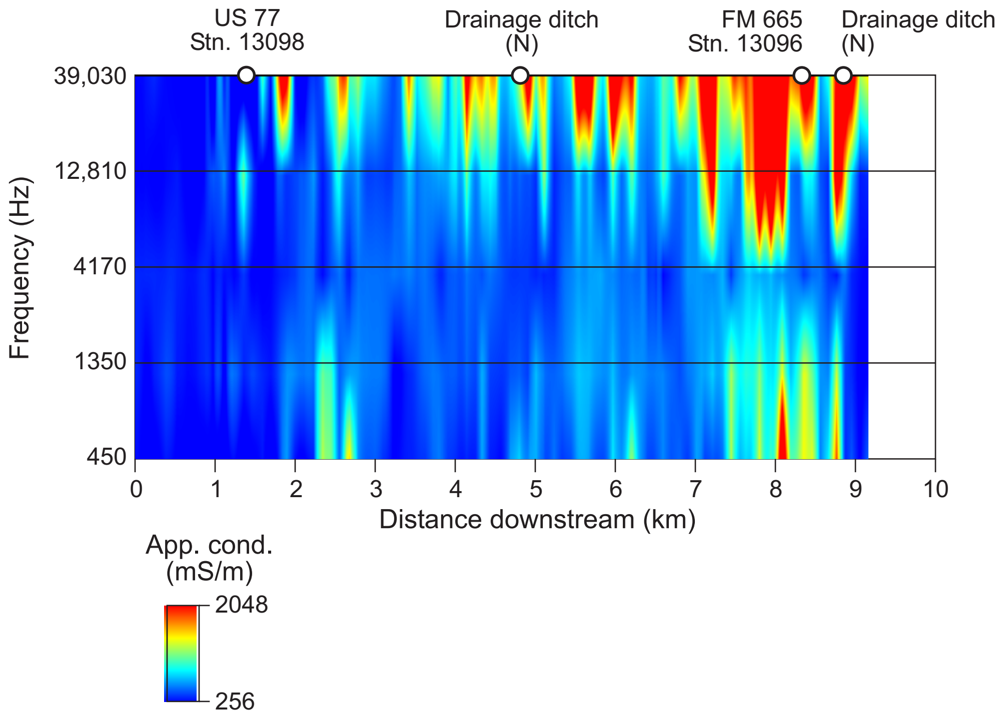

Figure 26. Combined apparent conductivity pseudosection along the Driscoll segment using all frequencies acquired during the airborne stream-axis survey. The shallowest-exploring frequency is along the top of the image and the deepest-exploring frequency is along the bottom.

FM 2826) and at the downstream end of the segment (FM 665) show large downstream increases in cation (calcium, magnesium, and sodium) and anion (chloride and sulfate) concentrations (fig. 27). Extremely high sodium and calcium concentrations imply either a seawater or produced water salinity source. Higher concentration of calcium than magnesium better matches the reported chemistry of produced water (higher concentration of calcium than magnesium) than that of Baffin Bay water (higher concentration of magnesium than calcium; Shipley, 1991).

Elevated apparent conductivities are evident across the Clara Driscoll field at all frequencies and at the North Clara Driscoll field at low to intermediate frequencies, suggesting that oilfield-related, near-surface salinization has occurred in these areas, probably largely from past surface discharge of produced water into pits and ditches. Assuming that there has been no significant surface discharge of produced water since the permitted practice ended in 1987, the most likely mechanism for infiltration of highly saline water into this creek segment is (1) infiltration of produced water into the shallow subsurface from pits and drainage ditches; (2) lateral migration of saline water through sandy Beaumont Formation channels; and (3) discharge as local, shallow-source base flow into Petronila Creek in places along the 7.7-km conductive segment.

In June 2005, we acquired a core from borehole NU-0501 on the upland surface in the Driscoll area (figs. 21 to 25) to examine whether there was evidence for subsurface infiltration of saline water. A conductivity log of the borehole, located about 160 m southwest of Petronila Creek, shows extremely high apparent conductivity at all depths below about 1 m, indicating the presence of highly saline pore fluid throughout the section (fig. 28). Poorly permeable silty clay was recovered from the surface to a depth of about 5 m. Below this was a wet, sandy horizon that is more than 1 m thick; the elevation of this horizon overlaps the estimated elevation of the floor of nearby Petronila Creek. Similar sandy horizons were observed near the base of the drainage ditch along County Road 18 (fig. 9). The sandy horizon overlies a poorly permeable stiff clay, both in the borehole and at the floor of the drainage ditch. Sandy horizons like these within the Beaumont Formation can serve as produced-water infiltration points along drainage ditches, lateral transport pathways, and discharge horizons along the creek.

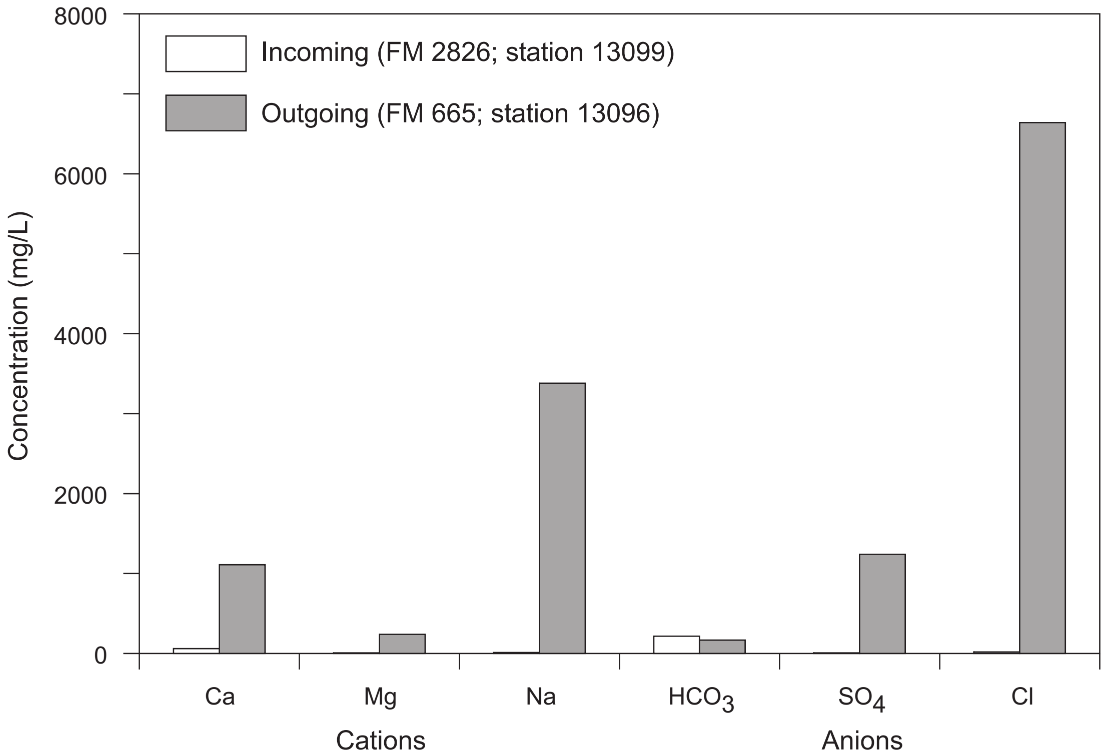

Figure 27. Major-ion concentrations in Petronila Creek samples taken upstream (incoming, location 1, station 13099, fig. 4) and downstream (outgoing, location 4, station 13096) from the Driscoll high-conductivity area in February 2005 (appendix B).

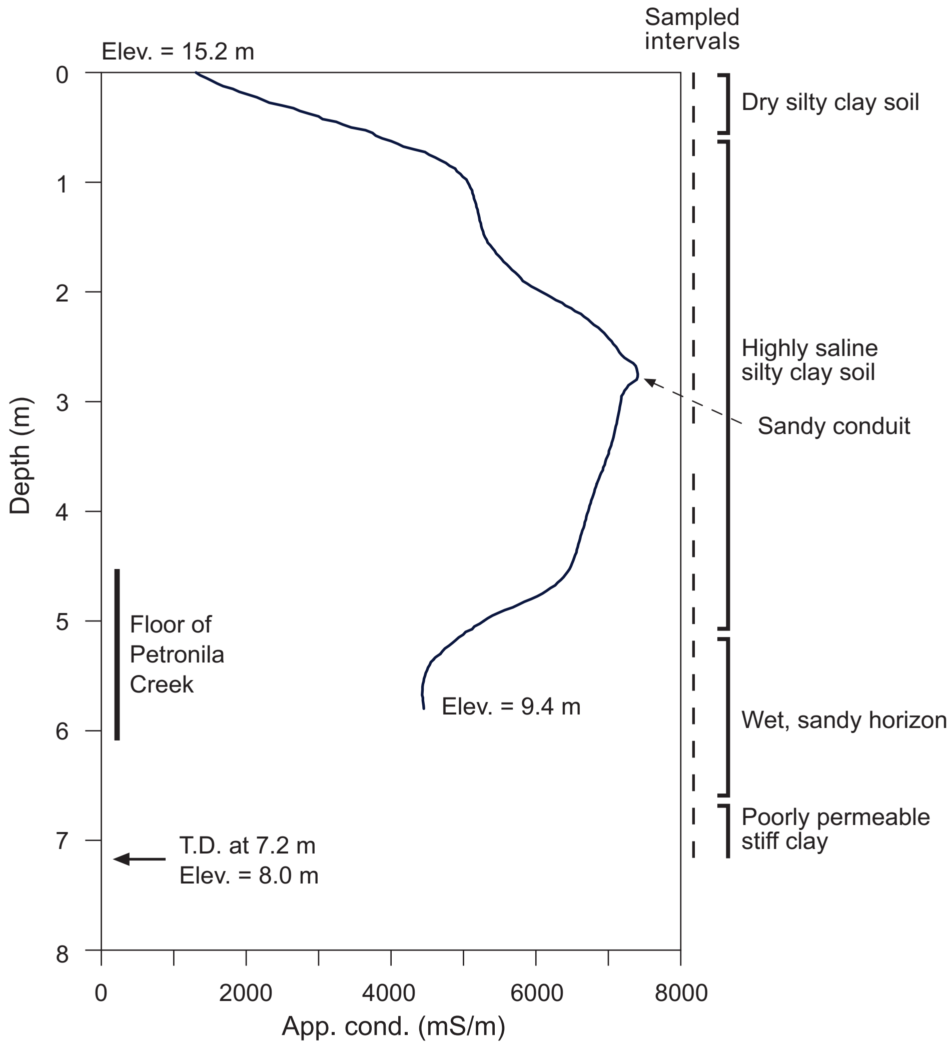

Figure 28. Apparent conductivity measured in borehole NU-0501 in the Driscoll high-conductivity area (figs. 21 to 25). The borehole is on the upland 160 m southwest of Petronila Creek. Sampled intervals and generalized soil descriptions are also shown.

Water sampling and analysis done by EA at the time of the airborne survey can be used to estimate salinity loading along this segment (fig. 29). At the upstream end at U.S. 77, flow on February 8, 2005 (two days after the airborne survey was completed) was 0.1 ft^3 at a total dissolved solids (TDS) concentration of 2460 mg/L (table 4). This translates to an incoming TDS load of 602 kg/day. At FM 665 at the end of the Driscoll conductive segment, flow was 0.562 ft^3 at 15,100 mg/L at station 13096, translating to an outgoing salinity load of 20,762 kg/day, an increase of about 20,160 kg/day. We attribute this loading dominantly to the local base flow mechanism described above. Similar increases are estimated for chloride and sulfate (table 4).

Concordia Area

The Concordia area encloses a 9-km-long segment of Petronila Creek that begins about 1 km downstream from FM 665 and continues to about 2 km downstream from FM 892 (fig. 16). Petronila Creek receives discharge from the drainage ditch along County Road 18 about 2 km from the upstream end of this segment. The County Road 18 ditch (fig. 9) crosses the Clara Driscoll Oil Field. A second drainage ditch enters Petronila Creek from the north about 1 km downstream from FM 892.

Average conductivities calculated from stream-axis EM data generally show the Concordia area to contain the most conductive segment of Petronila Creek (table 3). Conductivities at the two highest frequencies are particularly high, implying highly conductive near-surface strata beneath the creek. Stream-axis EM data on maps (fig. 16 to 20) and in cross section (fig. 30) show that the most conductive segment is about 6 km long, extending from the upstream limit of the Concordia area to a point about 2 km upstream from FM 892 at the highest frequency (figs. 20 and 30). Local conductivity highs are present to a short distance downstream from the drainage ditch below FM 892 (at 9 km, fig. 30). Highest values at the next highest frequency (12,810 Hz) cover a shorter distance (3 km long) that begins about 3 km from the upstream end of the Concordia segment (figs. 19 and 30).

Block survey maps most clearly depict elevated Concordia conductivities at the two highest frequencies (figs. 24 and 25), but conductivities are also high at lower frequencies in the same general

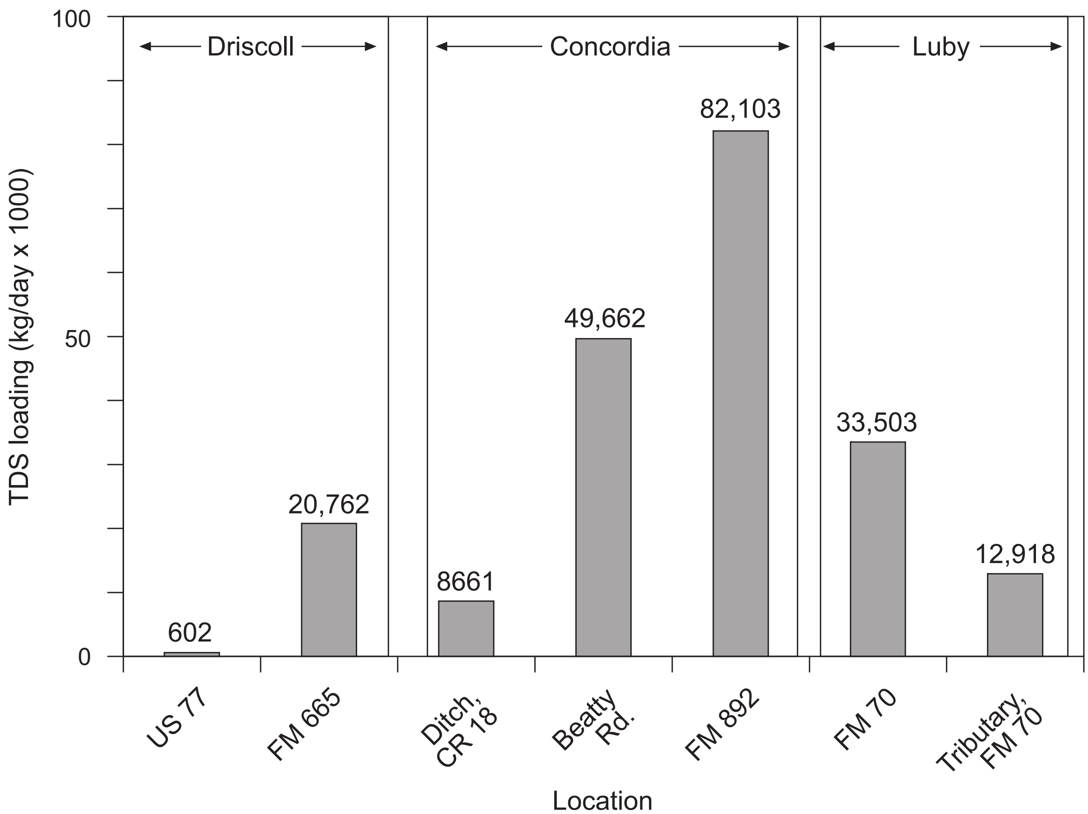

Figure 29. Petronila Creek TDS loading estimates for the Driscoll, Concordia, and Luby areas. Estimates are based on creek and tributary flow data and salinity concentrations measured by EA on February 8, 2005.

Table 4. TDS, chloride, and sulfate loading estimates based on flow and water-quality data collected by EA on February 8, 2005.

Location	**TDS (kg/day)**	**Chloride (kg/day)**	**Sulfate (kg/day)**
Driscoll area			
Incoming(station 13098, U.S. 77)	602	230	98
Outgoing (station 13096, FM 665)	20,762	10,037	1787
Change	+ 20,160	+ 9807	+ 1689
Concordia area			
Incoming (station 13096, FM 665)	20,762	10,037	1787
Contributing (station 13032, Co. Rd. 18)	8661	4746	856
Intermediate (station 13095, Beatty Rd.)	49,662	23,605	3985
Outgoing (station 13094, FM 892)	82,103	42,500	6761
Change	+ 61,341	+ 32,463	+ 4974
Luby area			
Incoming (station 13093, FM 70)	33,503	15,981	3,081
Contributing (station 13030)	12,918	7398	1292

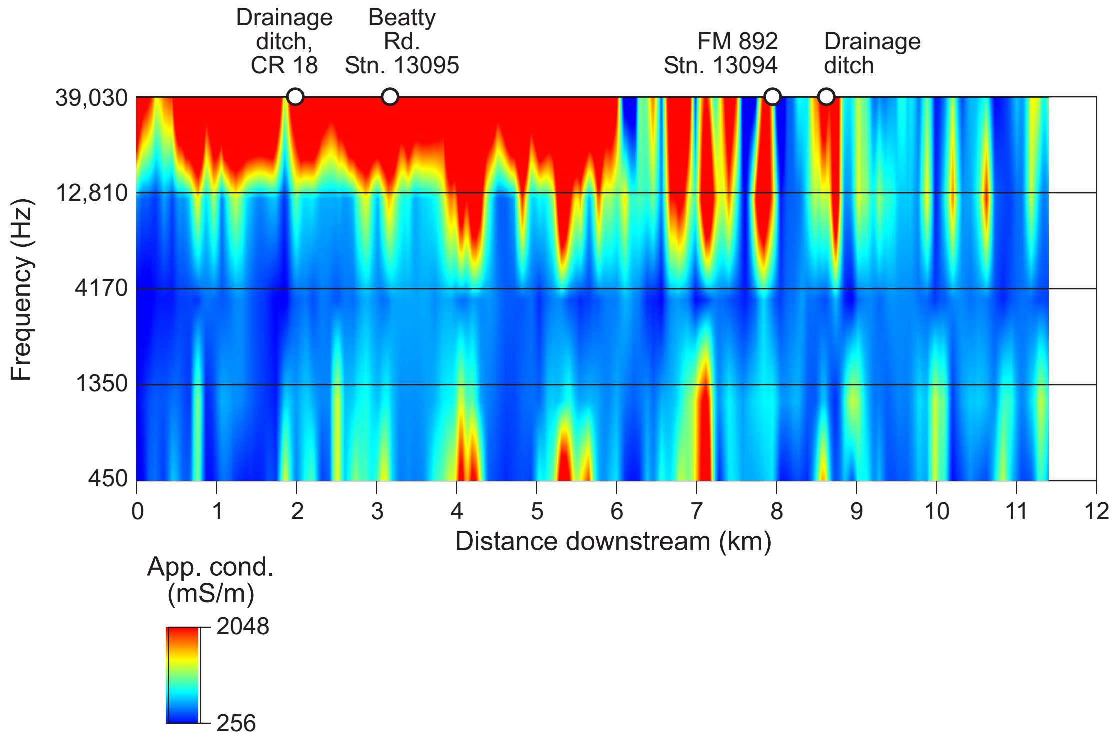

Figure 30. Combined apparent conductivity pseudosection along the Concordia segment using all frequencies acquired during the airborne stream-axis survey. The shallowest-exploring frequency is along the top of the image and the deepest-exploring frequency is along the bottom.

area on the south side of Petronila Creek (figs. 21 to 23). Each image also reveals high apparent conductivities associated with a drainage ditch roughly parallel to and south of the County Road 18 ditch. These high-conductivity lobes trend generally northeastward from this ditch toward Petronila Creek (fig. 23), intersecting the creek near water sampling sites on Beatty Road (station 13095, fig. 4) and FM 892 (station 13094).

Elevated conductivities between 0 and 10 km at the high, shallow-exploring frequencies indicate significant near-surface salinization. Decreasing conductivities with increasing exploration depth generally indicate near-surface rather than deep sources of salinity. EA measured elevated surface-water salinities at each sampling site in February 2005, including 35,400 mg/L TDS in the ditch along County Road 18, 16,200 mg/L at station 13095 at Beatty Road, and 17,000 mg/L at station 13094 at FM 892. Chemical analyses of water samples taken from Petronila Creek upstream and downstream from the Concordia high-conductivity segment show a slight downstream increase in major-ion concentrations that preserve the relative abundances present in the upstream sample (fig. 31). This suggests that produced oil-field water similar to that responsible for increasing Petronila Creek salinity along the Driscoll segment is also discharging into the creek in the Concordia segment.

There are relatively few oil and gas wells within the Concordia area, but at least two drainage ditches that carried water produced from wells farther west cross the area south of Petronila Creek. Both ditch systems are associated with local conductivity highs on the stream-axis line where they reach Petronila Creek, and the conductive areas on the apparent conductivity maps include these ditch systems. Based on the conductivity data, we interpret that the lobes of elevated conductivity south of Petronila Creek represent relatively shallow accumulations of saline produced water that was discharged into the drainage ditches when that practice was permitted and entered the subsurface along the ditches where they intersect sandy Beaumont Formation channels. This water has migrated laterally toward Petronila Creek, providing locally sourced saline base flow to Petronila Creek. We estimated salinity loading along the Concordia segment using EA's February 2005 sampling and analyses (fig. 29). Loading at the upstream end of the segment is represented by the 20,762 kg/day TDS value calculated at FM 665 (station 13096). At the Beatty Road crossing (station 13095) within the upper part of the

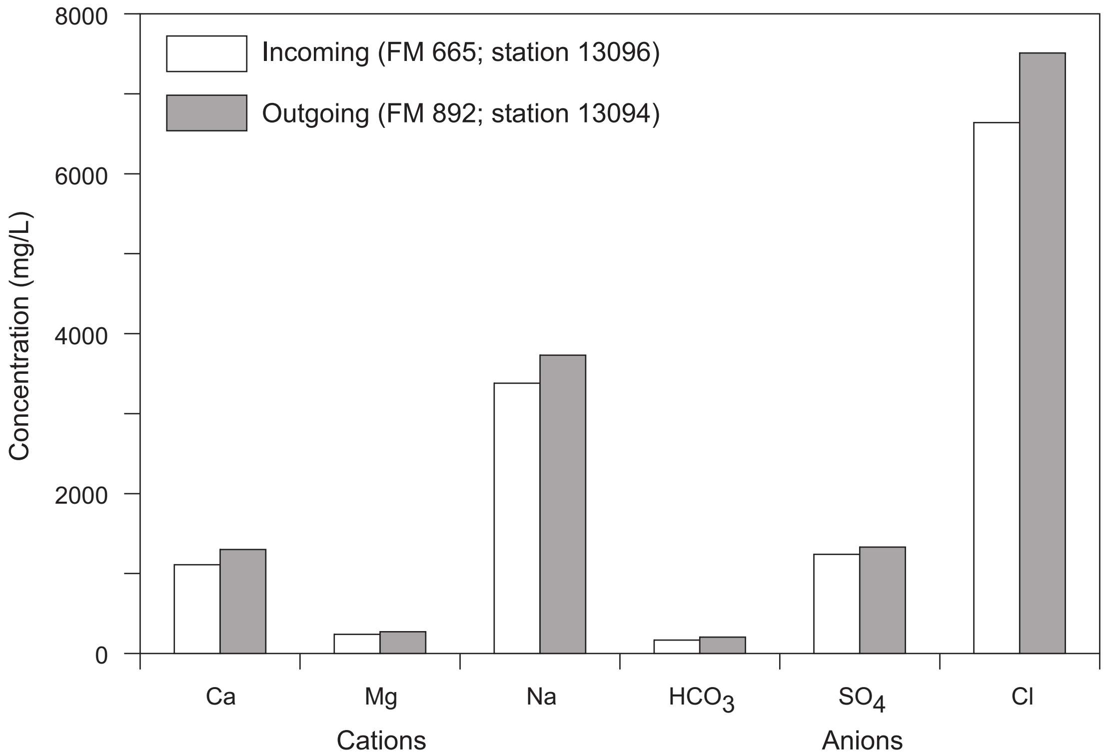

Figure 31. Major-ion concentrations in Petronila Creek samples taken upstream (incoming, location 4, station 13096, fig. 4) and downstream (outgoing, location 7, station 13094) from the Concordia high-conductivity area in February 2005 (appendix B).

Concordia segment, flow had increased to 1.253 ft^3 at 16,200 mg/L TDS, representing a TDS load of 49,662 kg/day, an increase of about 29,000 kg/day above the value at FM 665 (table 4). At FM 892 (station 13094) farther downstream within the Concordia segment, combining the 1.974 ft^3 flow with 17,000 mg/L TDS concentration translates to a TDS load of 82,103 kg/day, an increase of more than 32,000 kg/day from the Beatty Road crossing. Total loading increase along the Concordia segment was thus more than 61,000 kg/day. We interpret this increase, and similar large increases in chloride and sulfate loading (table 4), to be dominated by local-source, near-surface base flow from produced water that was once discharged into the two major drainage ditches crossing the area, entered the shallow subsurface along the ditches, and migrated toward the creek along sandy subsurface Beaumont Formation channels.

Luby Area

The Luby segment of Petronila Creek is the most downstream high-conductivity segment surveyed. It begins near the FM 70 bridge in southern Nueces County, reaching downstream about 10 km to the boundary of the survey area in Kleberg County (fig. 16). The upstream limit of this segment coincides with the upstream limit of estuarine mixing from the Baffin Bay-Laguna Madre estuarine system (Shipley, 1991). Petronila Creek crosses the southern part of the Luby Oil Field along the upper 4 km of this segment. A tributary stream joins Petronila Creek about 3 km downstream from FM 70. This tributary connects with a network of drainage ditches that cross the Luby Oil Field.

Stream-axis EM data acquired in the Luby area differ from those in the Driscoll and Concordia segments. Average conductivity is the lowest of the three segments at the highest frequency; instead, average conductivity peaks at lower frequencies in this segment (table 3). Stream-axis maps show a pronounced conductivity high at 450 and 1350 Hz (figs. 16 and 17), but little evidence of extensive areas of elevated conductivity at the shallowest-exploring frequency (fig. 20). The conductivity pseudosection (fig. 32) also is unique: it shows only minor, local areas of elevated conductivity between FM 70 and the Luby Oil Field tributary at the highest frequencies. More notable is an extended length of elevated conductivity best expressed in measurements at 1350 Hz (figs. 17 and 32) that reaches at least 7 km downstream from a point 1 km below FM 70.

Apparent conductivity patterns in the block survey are also striking, depicting a front of high conductivity at the lowest frequencies (figs. 21 and 22) that extends from the southeast boundary of the survey area to the FM 70 bridge. This pattern is absent from the higher frequencies (figs. 23 to 25), although apparent conductivities at the intermediate frequency (4170 Hz, fig. 23) are high in the Luby Oil Field area north of Petronila Creek.

Elevated near-surface conductivities are present locally and are associated with water samples having elevated TDS concentration (17,400 mg/L at station 13093 during EA's February 2005 sampling), but are not as extensive as in the Driscoll and Concordia areas. We acquired two water samples to assess water quality in the Luby segment, but both represent inflows to the segment (figs. 21 and 33). Major-ion concentrations in Petronila Creek at FM 70 at the upstream end of the segment are proportionately higher than those at FM 892 leaving the Concordia segment, suggesting either evaporative concentration of creek water or the addition of high-salinity water between the stations that is chemically similar to baseflow additions in the Driscoll and Concordia areas. Water sampled from the Luby Oil Field tributary also had similar Na-Cl dominated ionic ratios to Petronila Creek water in the Driscoll and Concordia areas, but had a slightly higher sulfate to chloride ratio.

There are insufficient data available to estimate possible TDS loading changes along this most downstream, coastal-influenced segment. At FM 70 (station 13093) at the upstream end of the segment, combining EA's February 2005 flow of 0.787 ft^3 with a TDS concentration of 17,400 mg/L translates to an incoming load of 33,503 kg/day (table 4). The reduction in TDS load of more than 48,000 kg/day from 82,103 kg/day at the downstream limit of the Concordia segment to the Luby segment is thus likely caused by flow losses along the creek.

There is relatively little evidence for shallow salinization along the Luby segment despite estuarine mixing. Minor near-surface salinization near the Luby Oil Field may be attributed to produced water reaching this segment along drainage ditches. More pronounced is deeper salinization indicated by elevated conductivity at the lower frequencies. We interpret these data to suggest that this area may

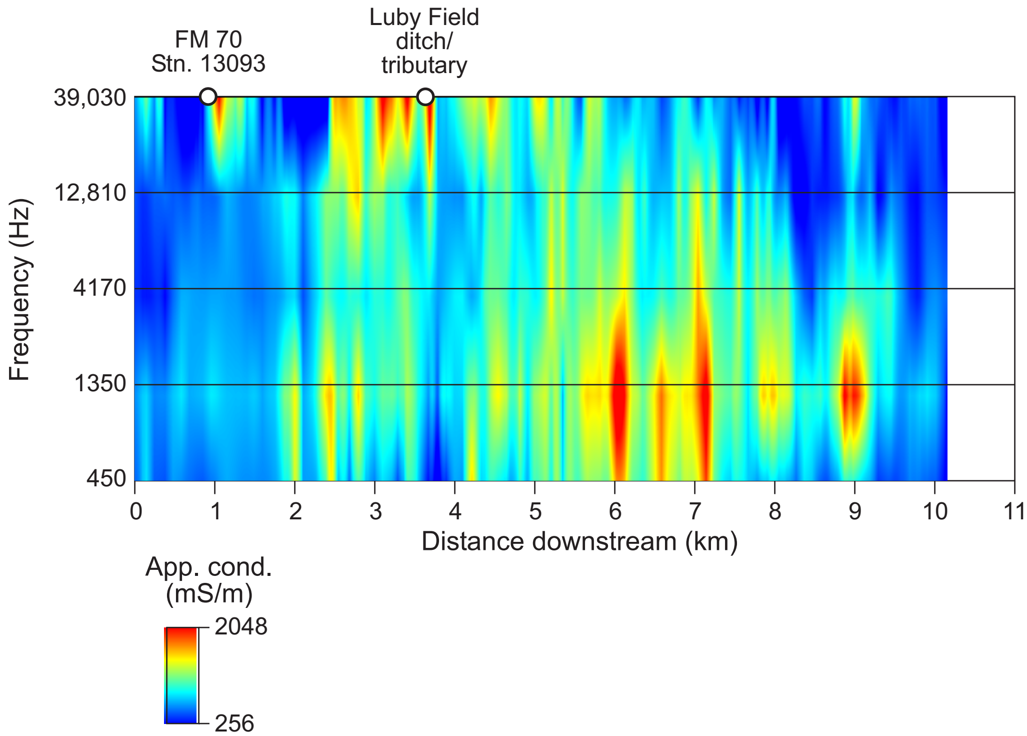

Figure 32. Combined apparent conductivity pseudosection along the Luby segment using all frequencies acquired during the airborne stream-axis survey. The shallowest-exploring frequency is along the top of the image and the deepest-exploring frequency is along the bottom.

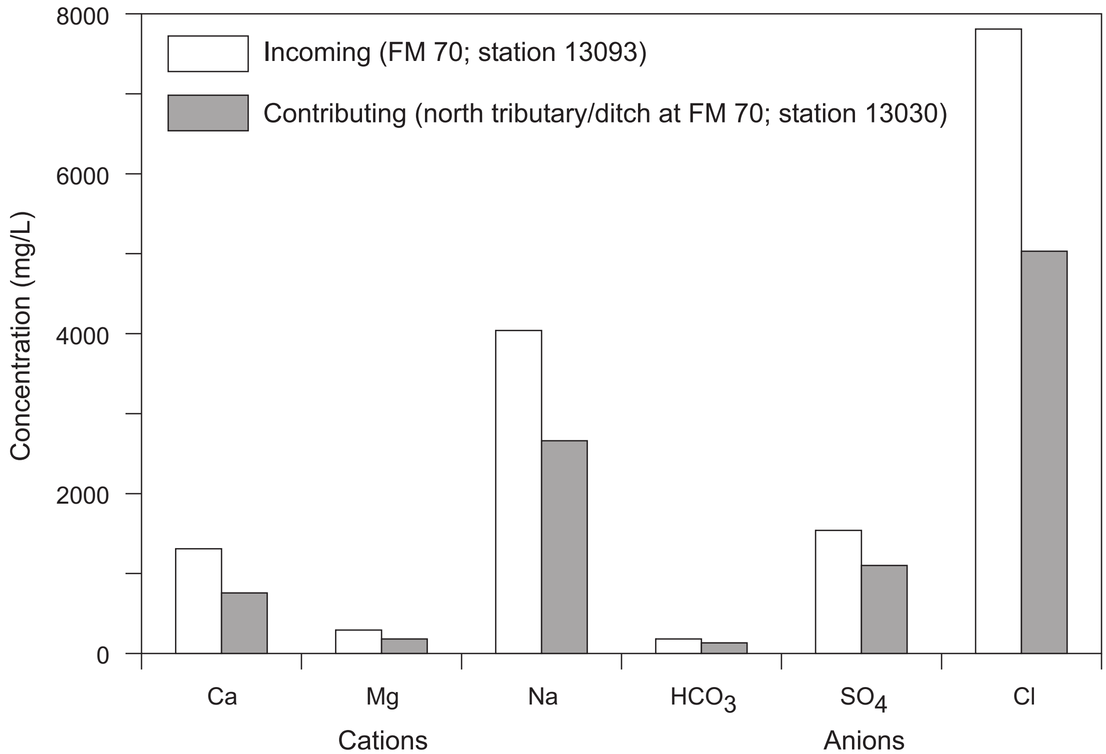

Figure 33. Major-ion concentrations in Petronila Creek and ditch/tributary samples taken along Petronila Creek near the upstream limit of the Luby high-conductivity area (incoming, location 8, station 13093, fig. 4) and along a tributary/ditch (contributing, location 9, station 13030) within the Luby area in February 2005 (appendix B).

mark the upstream limit of subsurface incursion of saline coastal water, rather than representing further significant addition of produced water to the stream environment.

CHLORIDE/BROMIDE MIXING MODELS

To further confirm whether elevated salinity in Petronila Creek in the Driscoll and Concordia areas is consistent with the addition of brine produced from area oil fields, we acquired and chemically analyzed a sample of brine produced from the Vicksburg reservoir in the Clara Driscoll Oil Field (location 10, fig. 4; appendix B). Conservative hydrochemical mixing models use the high solubility of chloride and bromide to demonstrate the potential that water samples with significant differences in salinity have mixed to produce water of intermediate salinity. Chloride and bromide are conservative in that they tend to remain in solution while other common ionic species (Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^{-}, and SO_4^{2-}) are more prone to participate in chemical reactions or other complexing behavior that affect their concentration in solutions through precipitation as solids or adsorption to electrically charged particulate matter (clay). The concentration of nonconservative ionic species in a mixture may not be the simple sum of the relative contributions from each of the end-member waters, but the concentration of conservative species will more faithfully reflect the proportions of the component end-members.

We constructed hydrochemical models (fig. 34) that mixed varying proportions of highly saline water, including brine from the Clara Driscoll Oil Field (chloride concentration 63,590 mg/L at location 10, fig. 4; appendix B) and water sampled from the County Road 18 ditch (location 5, chloride concentration 14,780 mg/L), with relatively fresh water from Petronila Creek upstream from the Driscoll area (chloride concentrations 19 or 838 mg/L, locations 1 or 2). The Petronila Creek samples (fig. 34) have similar bromide/chloride ratios over a wide range of chloride concentrations, suggesting that the samples are hydrochemically similar despite large changes in salinity. Petronila Creek samples become more saline downstream; the increasing salinity is accompanied by a small increase in Br/Cl values. This suggests that the samples represent varying degrees of mixing between relatively fresh, upstream creek water (lowest Cl concentrations) and waters with higher Br/Cl than any of the stream samples. Two

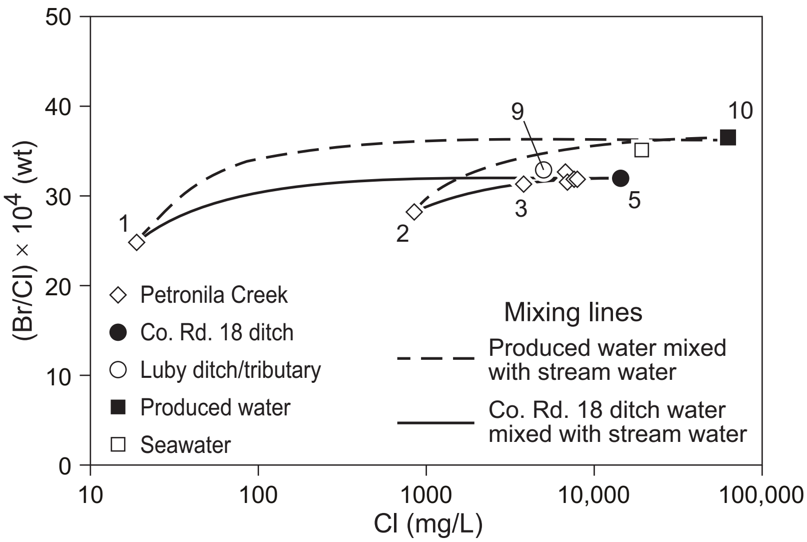

Figure 34. Bromide/chloride ratios (by weight) for Petronila Creek and tributary samples, seawater (Hem, 1985), and brine produced from the Clara Driscoll Oil Field in October 2005. Solid and dashed lines represent mixing lines generated from relatively fresh end-member samples taken upstream from the salinized area (locations 1 or 2, fig. 4; appendix B) and more saline end-member samples taken from the County Road 18 ditch (location 5) or from a tank battery in the Clara Driscoll Oil Field (location 10).

possible high-salinity components include seawater and brines similar to those produced from the Clara Driscoll Oil Field (fig. 34).

Despite the passage of several decades since large volumes of produced water were discharged to the ditches, pits, and streams and the possibility that the chemical signature of produced water acquired today from one reservoir might differ from that produced in the past from the same or different reservoirs, Petronila Creek samples fall near, but below, a mixing line that employs creek water from the Driscoll area (location 2) as a fresh endmember and produced water from the Clara Driscoll Oil Field (location 10) as the other endmember. Although not as saline, seawater has a bromide/chloride ratio that is similar to that of the produced brine and provides a similarly good fit as a possible saline endmember for Petronila Creek samples. Because of this, we cannot distinguish between seawater and recently produced brine as possible salinity sources.

Interestingly, the best mixing-line fit to Petronila Creek samples (fig. 34) is obtained when highly saline water collected from the County Road 18 ditch (location 5, fig. 4; appendix B) is mixed with relatively fresh water from the Driscoll area (location 2). This sample has a lower bromide/chloride ratio than either seawater or brine produced in 2005 from the Clara Driscoll Oil Field, and does not fall on any mixing line between either of these highly saline waters and fresher Petronila Creek samples. This observation supports an interpretation that saline water seeping into the County Road 18 ditch more closely matches an original, slightly lower bromide/chloride ratio of produced water that was discharged into the ditch during historical oil-field activities than it does bromide/chloride ratios of seawater or brine produced today. We conclude from this that produced water is the most likely dominant source of Petronila Creek salinity in the Driscoll and Concordia areas.

CONCLUSIONS

We conducted ground-based and airborne geophysical surveys and supporting hydrochemical sampling and analysis in the Petronila Creek area to delineate the extent and intensity of salinization and identify possible salinity sources that at times increase the TDS, chloride, and sulfate concentrations of segment 2204 beyond surface water quality standards for those constituents.

Results from the survey indicate that there are three high-conductivity areas downstream from U.S. 77 (the Driscoll, Concordia, and Luby areas) where ground salinization is likely to increase the salinity load of Petronila Creek. These high-conductivity creek segments are part of larger areas of elevated conductivity (and ground salinization) that extend hundreds of meters to several kilometers from the creek. At the most upstream high-conductivity area, the creek passes adjacent to the Clara Driscoll Oil Field where produced water was discharged into area ditches and creeks until non-tidal discharge was ended in 1987. Farther downstream in the Concordia area, past brine discharge into ditches crossing the area allowed produced water to infiltrate the shallow subsurface through sandy permeable horizons into the Beaumont Formation, where it appears to have migrated laterally toward the creek and can contribute highly saline ground water through creek-bank or creek-bed discharge. Significant TDS, chloride, and sulfate load gains occur along Petronila Creek across the Driscoll and Concordia segments.

The Luby area is farthest downstream, coinciding with the zone of estuarine mixing as part of the Baffin Bay estuarine complex. Salinity sources inferred here include (1) relatively deep subsurface infiltration of seawater in an inland direction; and (2) minor near-surface salinization associated with a tributary and ditch system that drains the Luby Oil Field.

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Alex Oren, Dak Darbha, Frank Funak, and Haoping Huang of Geophex acquired and processed airborne geophysical data. Ron Stewart and Tim Cole flew and maintained the helicopter used in the airborne survey. Fermin Munoz and Roy Staiger of the Texas Railroad Commission (District 4) and Rocky Freund of the Nueces River Authority helped guide field investigations and provided oil-field and surface-water data, Raed El-Farhan and Robert Oakes of The Louis Berger Group provided GIS data, Deborah Flados of the Texas Railroad Commission provided oil and gas well data, and Mark Kelly of EA Engineering, Science, and Technology provided guidance on field conditions in the Petronila Creek area. Steve Walden facilitated the project and reviewed work plans and deliverables.

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APPENDIX A: APPARENT GROUND CONDUCTIVITY MEASUREMENTS

Apparent conductivity measured in the Petronila Creek area, June 22 to 26, 2004. Conductivities (in millisiemens per meter, or mS/m) were measured using the Geonics EM31 ground conductivity meter in the vertical (VD) and horizontal (HD) dipole configurations. Location coordinates, determined using a GPS receiver, are in decimal degrees using the 1984 World Geodetic System (WGS 1984).

Location	**Latitude (degrees)**	**Longitude (degrees)**	**App. Con. (VD, mS/m)**	**App. Con (HD, mS/m)**	**Notes**
P002	27.67303	-97.72922	219	195	Edge of field east of Driscoll
P003	27.67298	-97.72904	209	226	"
P004	27.67293	-97.72884	221	236	"
P005	27.67289	-97.72864	212	221	"
P006	27.67283	-97.72845	233	233	"
P007	27.67278	-97.72826	226	223	"
P008	27.67272	-97.72806	226	223	"
P009	27.67267	-97.72787	244	231	"
P010	27.67263	-97.72767	222	224	"
P011	27.67257	-97.72748	208	220	"
P012	27.67252	-97.72729	209	225	"
P013	27.67246	-97.72709	230	237	"
P014	27.67241	-97.72690	231	238	"
P015	27.67235	-97.72670	226	230	"
P016	27.67230	-97.72650	212	213	"
P017	27.67224	-97.72630	217	214	"
P018	27.67219	-97.72612	247	237	"
P019	27.67213	-97.72593	240	247	"
P020	27.67208	-97.72574	257	268	"
P021	27.67203	-97.72556	261	286	"
P022	27.67198	-97.72541	304	317	Center of dirt road
P025	27.67737	-97.72430	233	202	Field adjacent to Petronila Creek
P026	27.67734	-97.72421	232	195	"
P027	27.67731	-97.72412	244	211	"
P028	27.67728	-97.72402	259	247	"
P029	27.67727	-97.72393	290	272	"
P030	27.67723	-97.72382	290	264	"
P031	27.67777	-97.72308	469	689	Petronila Creek; oilfield site
P032	27.67780	-97.72297	381	697	"
P033	27.67781	-97.72279	375	691	"
P034	27.67782	-97.72270	322	769	"
P035	27.67779	-97.72248	491	836	"
P036	27.67777	-97.72238	362	824	"
P037	27.67781	-97.72228	563	700	"
P038	27.67780	-97.72218	371	616	"
P039	27.67764	-97.72291	291	555	Well site above Petronila Creek
P040	27.67758	-97.72285	393	770	"
P041	27.67748	-97.72282	395	891	"
P042	27.67740	-97.72280	399	889	"
P043	27.67730	-97.72277	288	430	"

P044	27.67722	-97.72274	232	570	“
P045	27.67716	-97.72271	260	238	“
P046	27.67747	-97.72306	417	542	Well site; dry ponded area
P047	27.67865	-97.71568	257	269	Dirt road adjacent to Petronila Creek
P048	27.67883	-97.71572	209	210	“
P049	27.67900	-97.71577	182	197	“
P051	27.67918	-97.71584	196	216	“
P052	27.67935	-97.71591	207	221	“
P053	27.67952	-97.71597	197	247	“
P054	27.68316	-97.74339	202	168	Petronila Creek; downstream from U.S. 77
P055	27.68312	-97.74329	205	177	“
P056	27.68298	-97.74321	272	235	“
P057	27.68297	-97.74317	278	241	“
P058	27.68289	-97.74310	269	283	“
P059	27.68287	-97.74297	275	314	“
P060	27.68286	-97.74288	327	290	“
P061	27.68280	-97.74283	283	350	“
P062	27.68325	-97.74402	203	250	Petronila Creek; at U.S. 77 bridge
P063	27.68324	-97.74368	150	150	“
P064	27.68960	-97.74160	203	199	Field south of Coastal Bend Youth City
P065	27.68967	-97.74178	211	183	“
P066	27.68976	-97.74198	209	171	“
P067	27.68983	-97.74215	193	170	“
P068	27.68992	-97.74232	182	165	“
P069	27.69000	-97.74252	184	155	“
P070	27.69007	-97.74271	201	154	“
P071	27.69017	-97.74287	206	188	“
P072	27.69023	-97.74306	230	241	“
P073	27.69031	-97.74325	219	210	“
P074	27.69037	-97.74345	172	196	“
P075	27.69044	-97.74362	143	152	“
P076	27.69051	-97.74381	122	125	“
P077	27.69056	-97.74401	131	116	“
P078	27.66105	-97.75422	366	300	Ditch along County Road 18
P079	27.66113	-97.75441	382	302	“
P080	27.65993	-97.75041	440	385	“
P081	27.65996	-97.75041	451	345	“
P082	27.65889	-97.74649	379	350	“
P083	27.65780	-97.74250	391	446	“
P084	27.65675	-97.73860	390	470	“
P085	27.65550	-97.73425	330	756	“
P086	27.65541	-97.73482	258	242	Along dirt road south of County Road 18
P087	27.65522	-97.73486	245	275	“
P088	27.65505	-97.73493	159	197	“
P089	27.65490	-97.73499	228	230	“
P090	27.65472	-97.73503	216	215	“
P091	27.65456	-97.73514	250	233	“
P092	27.65435	-97.73517	237	226	“
P093	27.65419	-97.73521	218	229	“
P094	27.65403	-97.73526	216	221	“
P095	27.65389	-97.73534	201	206	“
P096	27.65471	-97.73132	420	738	Ditch along County Road 18
P097	27.65342	-97.72709	376	1065	“
P098	27.65256	-97.72361	367	672	“

P099	27.65130	-97.71934	441	640	“
P101	27.66908	-97.69605	167	165	Ditch along FM 665
P102	27.66517	-97.70230	276	796	Petronila Creek at FM 665
P103	27.66535	-97.70226	455	700	“
P104	27.73338	-97.77972	173	179	Pintas Creek
P105	27.71788	-97.75979	160	192	Petronila Creek
P106	27.72529	-97.74949	184	151	County Road 30
P107	27.72528	-97.74929	182	154	“
P108	27.72528	-97.74908	185	152	“
P109	27.72525	-97.74888	170	135	“
P110	27.72525	-97.74868	273	396	“
P111	27.72525	-97.74848	153	158	“
P112	27.72526	-97.74828	123	115	“
P113	27.72525	-97.74808	128	145	“
P114	27.72525	-97.74786	149	112	“
P115	27.72526	-97.74767	144	191	“
P116	27.59213	-97.60996	345	470	Unnamed tributary to Petronila Creek
P117	27.57916	-97.62711	402	450	Petronila Creek at old FM 70 crossing
P118	27.57969	-97.60368	408	403	Lease road south of FM 70
P119	27.57986	-97.60377	324	494	“
P120	27.58002	-97.60395	315	280	“
P121	27.57949	-97.60402	421	448	Road to Petronila Creek
P122	27.57932	-97.60404	371	385	“
P123	27.57912	-97.60407	365	400	“
P124	27.57895	-97.60411	338	391	“
P125	27.57867	-97.60533	416	615	Petronila Creek
P127	27.59209	-97.62249	417	408	Dirt road south of County Road 10
P128	27.59192	-97.62248	253	414	“
P129	27.59173	-97.62250	386	400	“
P130	27.59156	-97.62249	393	418	“
P131	27.59137	-97.62250	381	378	“
P132	27.59120	-97.62249	355	354	“
P133	27.59101	-97.62249	342	342	“
P134	27.59083	-97.62249	352	354	“
P135	27.59218	-97.66414	337	410	Unnamed creek/ditch
P136	27.59207	-97.66404	296	411	“
P137	27.59457	-97.66393	298	295	“
P138	27.60832	-97.68988	402	735	Ditch at FM 3354
P146	27.79769	-97.82130	118	95	Agua Dulce Creek at park
P147	27.68735	-97.71901	410	850	Barren area traverse; center point
P148	27.68727	-97.71899	404	783	Barren area traverse
P149	27.68717	-97.71895	475	963	“
P150	27.68709	-97.71894	607	893	“
P151	27.68700	-97.71890	396	642	“
P152	27.68691	-97.71886	391	892	“
P153	27.68684	-97.71881	419	778	“
P154	27.68681	-97.71881	479	675	“
P155	27.68676	-97.71876	420	620	“
P156	27.68667	-97.71872	428	478	“
P157	27.68659	-97.71867	400	428	South edge of barren area
P158	27.68651	-97.71864	372	413	Barren area traverse
P159	27.68643	-97.71862	385	401	“
P160	27.68634	-97.71859	367	389	“
P161	27.68625	-97.71855	332	336	“

P162	27.68616	-97.71852	350	300	“
P163	27.68743	-97.71906	455	775	“
P164	27.68751	-97.71910	503	734	“
P165	27.68760	-97.71913	462	754	“
P166	27.68769	-97.71917	400	529	“
P167	27.68778	-97.71921	309	466	“
P168	27.68786	-97.71920	302	346	North edge of barren area
P169	27.68795	-97.71923	282	277	Barren area traverse
P170	27.68802	-97.71929	292	260	“
P171	27.68810	-97.71936	307	216	“
P172	27.68818	-97.71941	285	252	“
P173	27.68827	-97.71942	268	259	“
P174	27.68836	-97.71945	291	262	“
P175	27.68843	-97.71949	283	244	“
P176	27.68852	-97.71952	277	258	“
P177	27.68860	-97.71956	313	244	“
P178	27.68871	-97.71956	252	232	“

APPENDIX B: HYDROCHEMICAL ANALYSES

Laboratory analytical results for Petronila Creek, ditch and tributary, and produced-water samples collected from the Petronila Creek basin. Sample locations shown on fig. 4. All analyses by the Kansas Geological Survey.

Sample	Lat. (deg)	Long. (deg)	Date	Sp. C. uS/cm	Lab. pH	SiO2 (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Sr (mg/L)	CO3 (mg/L)	HCO3 (mg/L)	SO4 (mg/L)	Cl (mg/L)	NO3-N (mg/L)	Br (mg/L)	B (mg/L)	TDS (mg/L)
1	27.7396	-97.7639	2/8/05	415	8.55	5.9	61	6	12	11.4	0.25	3.7	217	6	19	0.20	0.046	0.08	233
2	27.6830	-97.7436	2/8/05	3,830	8.00	19.1	307	40	447	15.1	1.80	0.00	419	424	838	0.29	2.37	1.32	2,300
3	27.6818	-97.7415	2/8/05	12,900	7.80	27.3	789	124	1,960	11.5	6.92	0.00	361	1,050	3,800	1.11	11.9	3.89	7,970
4	27.6649	-97.7025	2/8/05	20,700	7.65	<2.7	1,110	238	3,380	20.1	18.1	0.00	167	1,240	6,640	0.95	21.8	6.76	12,770
5	27.6506	-97.7160	2/8/05	41,600	8.05	<5.0	1,480	432	8,600	34.3	33.4	0.00	123	2,630	14,780	1.45	47.2	13.3	28,100
6	27.6418	-97.6872	2/8/05	21,600	7.90	16.1	1,180	249	3,570	16.1	19.2	0.00	200	1,280	6,940	1.69	21.9	6.91	13,400
7	27.6170	-97.6639	2/8/05	22,800	7.70	14.7	1,300	272	3,730	16.2	19.6	0.00	204	1,330	7,510	1.08	23.9	6.58	14,330
8	27.5837	-97.6283	2/8/05	23,700	7.85	17.4	1,310	293	4,040	21.2	19.4	0.00	181	1,540	7,810	0.84	24.8	7.60	15,180
9	27.5853	-97.6069	2/8/05	15,800	7.60	13.0	757	181	2,660	27.1	11.6	0.00	132	1,100	5,030	1.02	16.6	6.24	9,870
10	27.6649	-97.7276	10/24/05	139,000	6.00	42.2	3,360	451	33,500	264	592	0.00	137	<5	63,590	na	231	36.8	102,100