

RECONNAISSANCE GEOPHYSICAL INVESTIGATIONS OF SALINIZATION
ALONG THE UPPER COLORADO RIVER (TMDL SEGMENT 1426),
COKE AND RUNNELS COUNTIES, TEXAS

by

Jeffrey G. Paine and Edward W. Collins
Bureau of Economic Geology
John A. and Katherine G. Jackson School of Geosciences
The University of Texas at Austin

Mail address:
University Station, Box X
Austin, Texas 78713-8924

Street address:
J. J. Pickle Research Campus, Building 130
10100 Burnet Road
Austin, Texas 78758-4445
jeff.paine@beg.utexas.edu

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P.O. Box 13087
MC 150
Austin, Texas 78711-3087

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INTRODUCTION

This report summarizes a reconnaissance investigation of surface-water salinity and shallow electrical ground conductivity along segment 1426 of the upper Colorado River near San Angelo, Texas (fig. 1). Segment 1426 extends more than 100 km from its upstream limit at the Robert Lee Dam impounding E. V. Spence Reservoir (Lake Spence) in Coke County to several kilometers downstream from the Mustang Creek confluence below Ballinger in Runnels County. Several governmental agencies have monitored and analyzed surface water quality along segment 1426, including the Lower Colorado River Authority, the Upper Colorado River Authority, the Colorado River Municipal Water District, the U.S. Geological Survey, and the Texas Commission on Environmental Quality (TCEQ) and its subcontractors (EA Engineering, Science, and Technology, 2002). Surface-water monitoring has revealed periodic and repeated high salinity values at several monitoring sites along this segment, at times exceeding the 2,000 milligrams per liter (mg/L) criterion for total dissolved solids (TDS). Other related constituents of concern include chloride and sulfate (EA Engineering, Science, and Technology, 2002).

The Colorado River lies within a broad alluvial valley eroded into Permian stratigraphic units on the eastern flank of the Permian Basin (Eifler, 1975; Kier and others, 1976). The youngest bedrock units crop out in the Lake Spence area, including sandstones, shales, and dolomites of the Whitehorse Group and Quartermaster Formation. These units, as well as the underlying Blaine Formation shales, sandstones, and dolomite and the Clear Fork Group shales and dolomites that crop out between Robert Lee and Ballinger, include gypsum-bearing intervals whose dissolution likely contributes to degraded surface-water and ground-water quality in the area. Near and downstream from Ballinger, these evaporite-bearing strata are eroded away; geologic units at the surface in the southeast part of the study area are older Permian strata (Leuders, Talpa, Grape Creek, and Bead Mountain formations) composed dominantly of limestone with thin shale interbeds (fig. 2). Significant widths and thicknesses of unconsolidated to semiconsolidated Pleistocene and Holocene sand, gravel, silt, and clay have been deposited within the Colorado River alluvial valley. In some places, the bed of the river flows directly on Permian bedrock; in others, the river flows on a veneer of unconsolidated alluvial deposits.

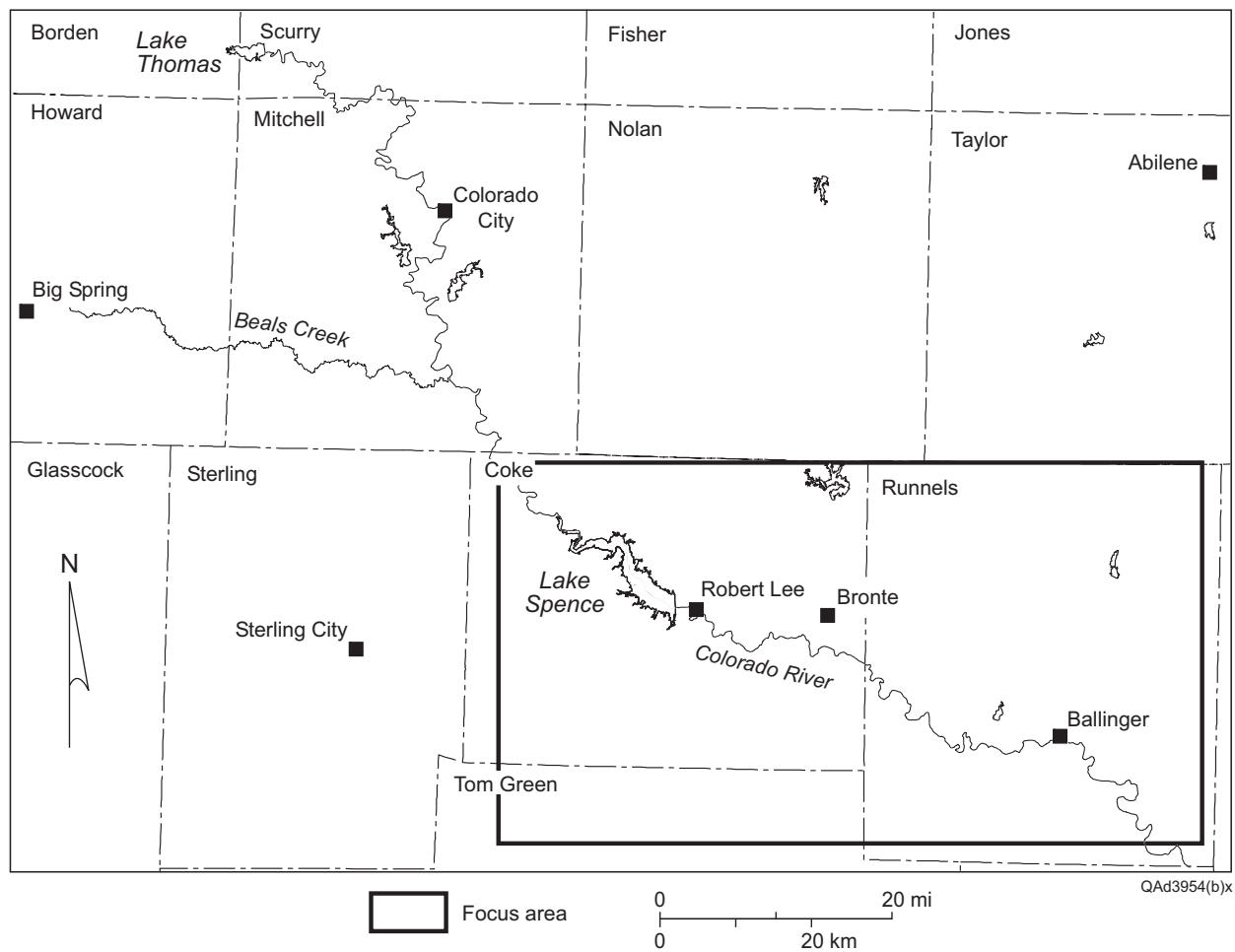


Figure 1. Map of the upper Colorado River region and the study area surrounding TMDL segment 1426, west Texas.

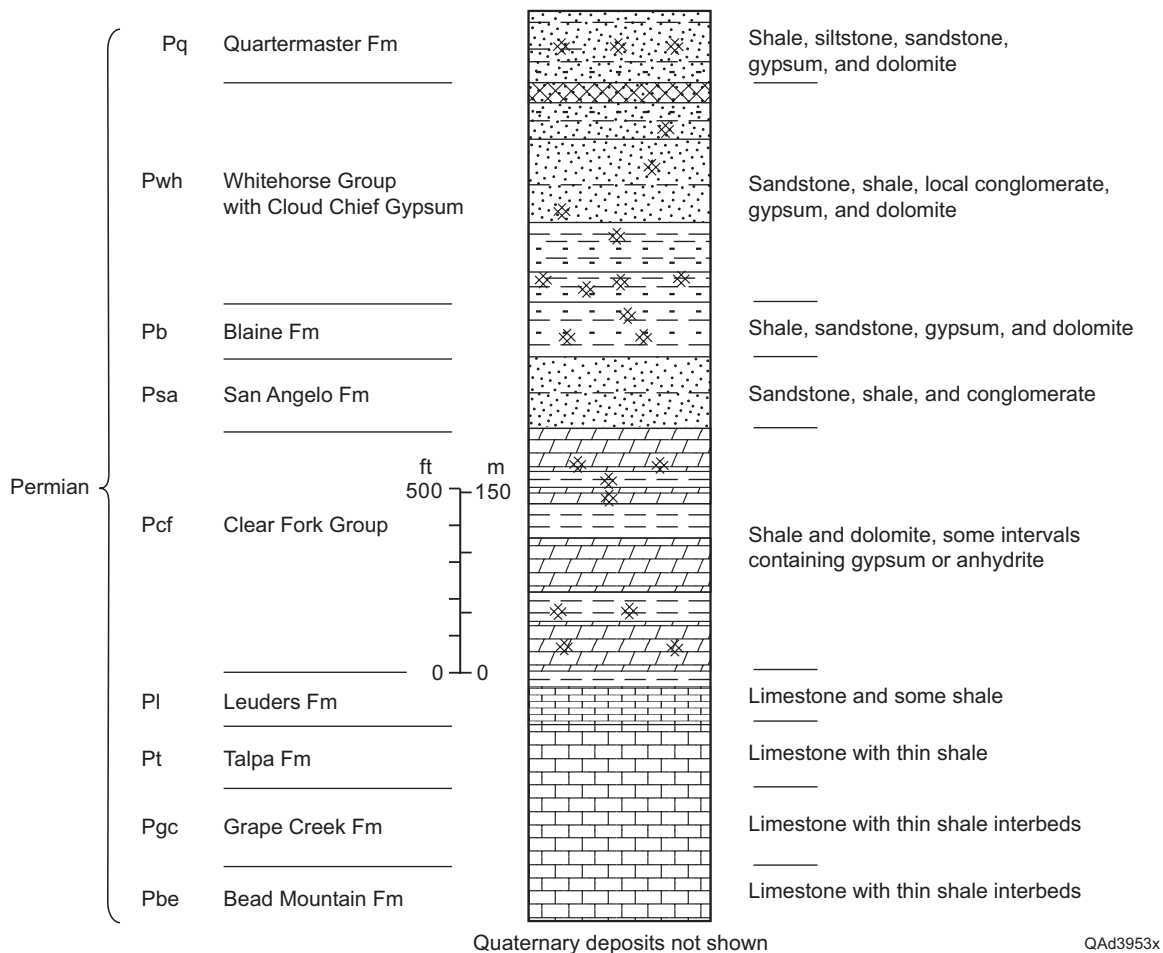


Figure 2. Generalized stratigraphic column and rock type for Permian units cropping out along the Colorado River in Coke and Runnels counties. Because these units dip regionally to the west, outcropping units become older in the downstream direction.

There have been many investigations of factors affecting relatively poor surface- and ground-water quality along this segment of the Colorado (including Mount and others, 1967; Leifeste and Lansford, 1968; Richter and others, 1990; Slade and Buszka, 1994; Paine and others, 1999). Most previous studies attribute degraded surface- and ground-water quality in the upper Colorado River area to a combination of effects, including (a) natural dissolution of evaporite deposits and subsequent migration of saline water to the surface, and (b) oilfield-related introduction of highly saline formation water into the surface and near-surface environment through surface discharge of produced water into pits or through unplugged oil and gas wells.

This study uses instruments based on the electromagnetic induction method to acquire supplemental information on the electrical conductivity of the shallow subsurface along and near the Colorado River. Most sediment, soil, and rock types are poor electrical conductors (McNeill, 1980a). The electrical conductivity of water is strongly influenced by its TDS concentration (Robinove and others, 1958); its conductivity increases almost linearly as TDS increases. When saline water infiltrates generally nonconductive strata, the bulk conductivity of the strata increases as the salinity of the pore water increases. Conductivity measurements are thus a useful proxy for salinization intensity in most strata.

METHODS

We supplemented available surface-water quality data with reconnaissance measurements of the electrical conductivity of the ground and surface water 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. In places along the Colorado River, there was sufficient water depth to allow travel by canoe to isolated stream and tributary segments. Elsewhere, stream access was by foot from road or bridge crossings. A hand-held GPS receiver provided locations for all ground- and water-conductivity measurements.

EM Survey

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, 1973; 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. 3) 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 millisiemens/m (mS/m) to 1,000 mS/m.

We acquired ground conductivity measurements at 219 sites along the upper Colorado River, its significant tributaries, and around Lake Spence on July 19 to 22 and August 2 to 3, 2004 (appendix A). At most locations, we acquired several measurements at various intervals along the stream bank (if the stream was flowing) or along the stream axis (if the stream was dry).

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 water-quality data.



Figure 3. Geonics EM31 ground conductivity meter.

Water Conductivity and TDS

We measured the electrical conductivity of water samples at 17 locations along the upper Colorado River and its tributaries (appendix B) using a Corning Checkmate 90 conductivity and TDS probe (fig. 4). All measurements were taken on August 2 and 3, 2004. This instrument measures the temperature and electrical conductivity of the water sample and calculates the resulting TDS concentration. All temperature, conductivity, and TDS measurements were entered into a geographic information system database for comparison with ground conductivity data.

RESULTS

We supplemented existing data on surface water quality in the upper Colorado River area with (a) reconnaissance measurements of water conductivity and TDS concentration and (b) measurements of apparent ground conductivity. These complementary data sets reveal a snapshot of salinity in the Colorado River and its tributaries and impoundments and likely salinity source areas in alluvial deposits adjacent to the river.

Surface Water Measurements

Surface-water salinity measured during the ground conductivity survey in August 2004 revealed highly variable water quality across the area. Lake Spence, the source of most of the Colorado River water between Robert Lee and Ballinger, had a slightly saline TDS concentration of 1470 milligrams per liter (mg/L) at the Lakeview Recreation Area on the north shore of the lake (fig. 5; location C187, appendix B). Colorado River water flowing into Lake Spence was considerably less saline at a TDS value of 590 mg/L (area B, fig. 5; location C236, appendix B) despite flowing through alluvial deposits with efflorescence (evaporite mineral crusts) and a dense growth of salt cedar. Runoff from recent rainfall may have temporarily lowered the TDS concentration of the Colorado River in this area.



Figure 4. Measuring water temperature, conductivity, and total dissolved solids (TDS) concentration on Mustang Creek using a Corning Checkmate 90 probe.

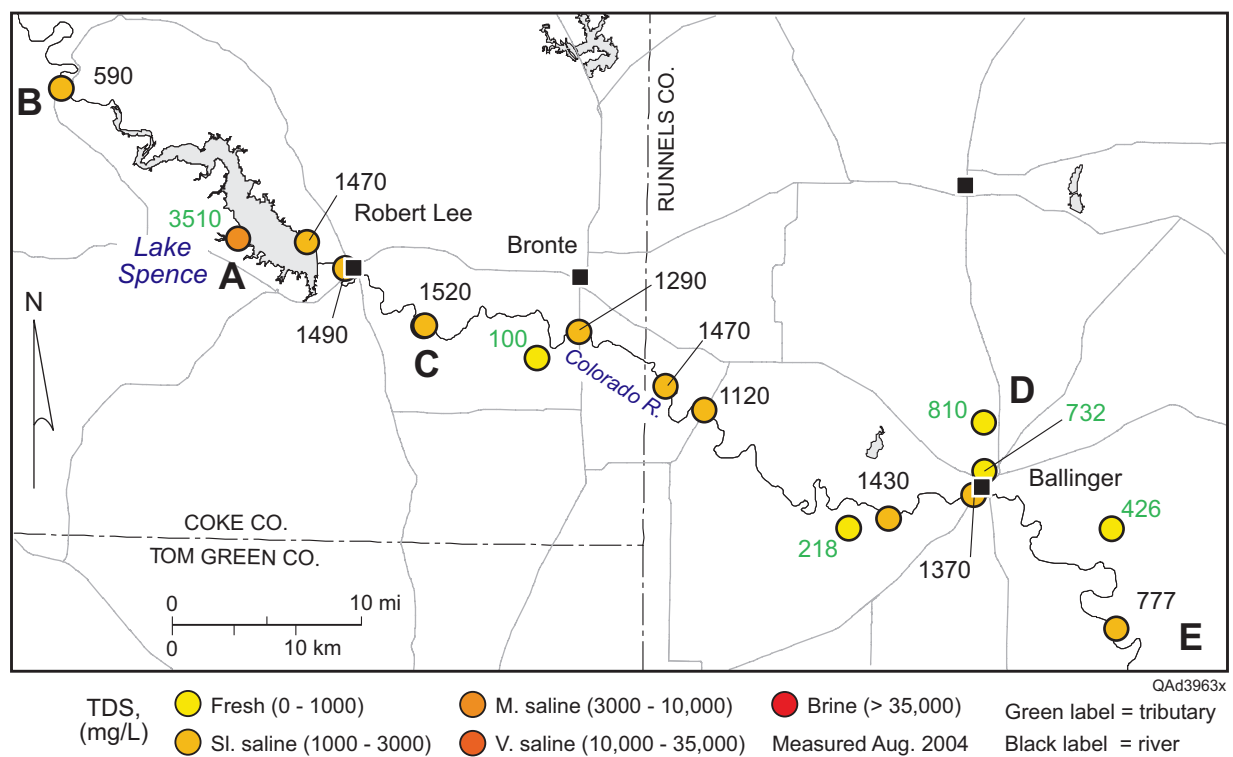


Figure 5. Map of the upper Colorado River segment 1426 study area depicting TDS concentration measured in August 2004 (appendix B).

At Salt Creek on the southern shore of Lake Spence, we measured a higher, moderately saline TDS concentration of 3510 mg/L in ponded water. The stream name, its salinity, and the presence of gypsum rock fragments in the stream bed all suggest that Salt Creek contributes to the elevated salinity of Lake Spence.

We sampled flowing Colorado River water at nine locations downstream from Lake Spence (fig. 5; appendix B). Upstream from Ballinger (above the confluence with Elm Creek), measured TDS concentrations were similar to those measured in Lake Spence, ranging from 1120 mg/L at the FM 3115 bridge (fig. 5; location C194, appendix B) to 1520 mg/L near a gravel quarry where efflorescence was noted on alluvial deposits adjacent to the river (area C, fig. 5; location C191, appendix B). At Ballinger, Elm Creek contributed a significant amount of fresh water (732 to 810 mg/L TDS, fig. 5; locations C196 and C197, appendix B) to the Colorado River. Downstream from Ballinger at the Runnels County Road 129 bridge, Colorado River water was fresh at 777 mg/L (area E, fig. 5; location C206, appendix B).

Measurements of TDS concentration taken in ponded water along minor, non-flowing Colorado River tributaries were relatively fresh, ranging from 100 mg/L on Live Oak Creek south of Bronte (fig. 5; location C228, appendix B) to 426 mg/L on Mustang Creek near Ballinger (fig. 5; location 203, appendix B). Neither Elm Creek nor these tributaries appear to contribute significant amounts of highly saline water to the Colorado River despite draining areas where significant hydrocarbon exploration and production has occurred.

Ground Conductivity Measurements

We acquired ground conductivity measurements at 219 representative sites along the Colorado River, in tributary stream beds, and around Lake Spence to better understand the extent and intensity of ground salinization and its possible contribution to elevated salinity concentrations in the Colorado River along TMDL segment 1426 (figs. 6 and 7; appendix A).

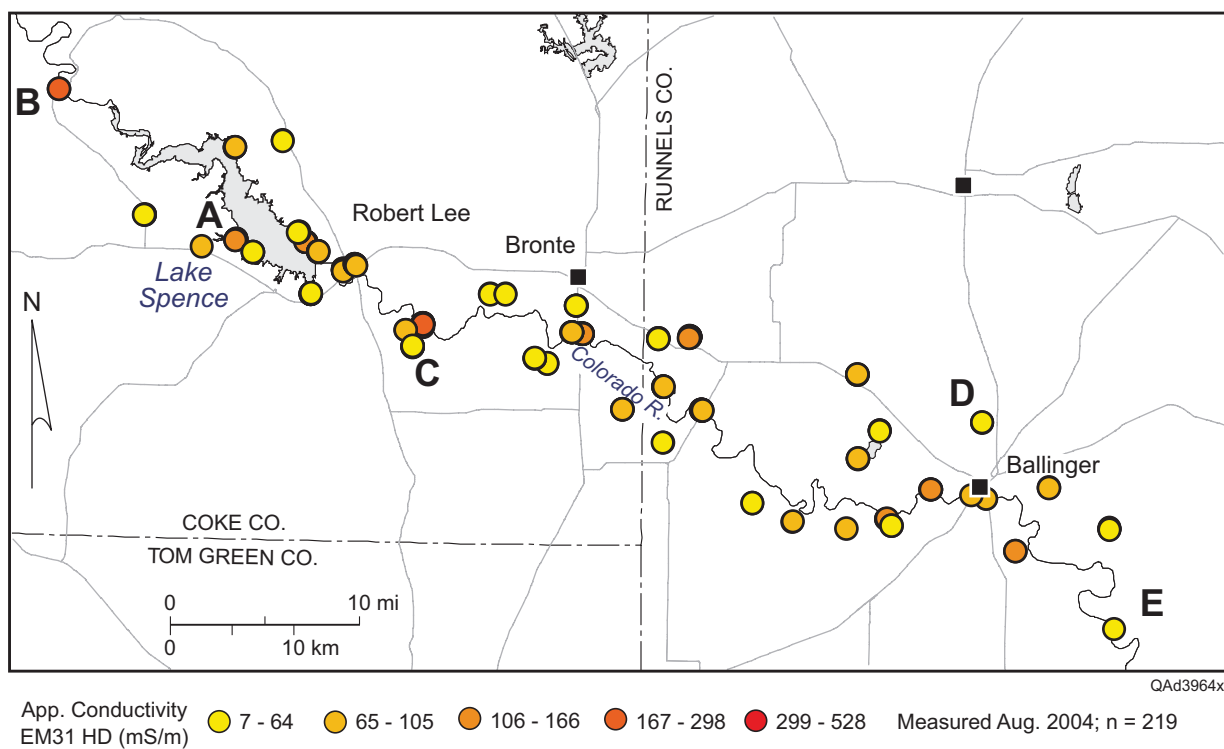


Figure 6. Apparent ground conductivity measured using an EM31 in the horizontal dipole (HD) mode.

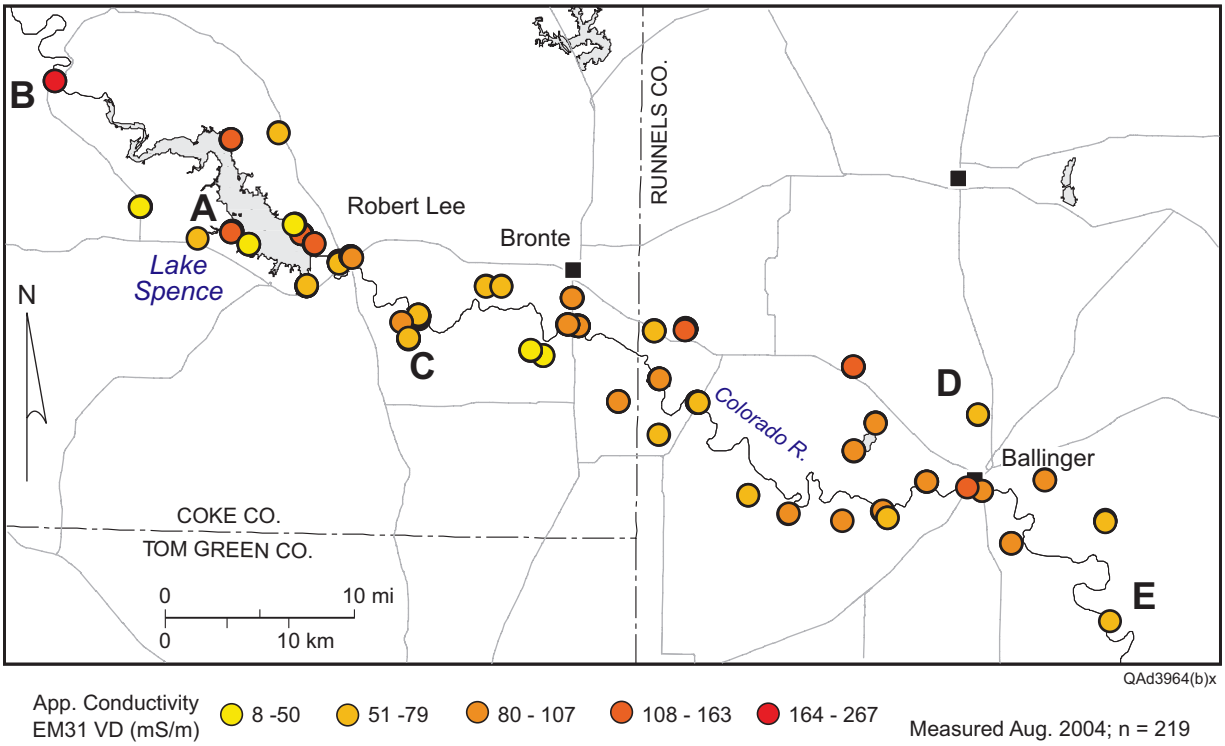


Figure 7. Apparent ground conductivity measured using an EM31 in the vertical dipole (VD) mode.

In general, measured apparent ground conductivity is relatively low in this area. In the horizontal dipole (HD) instrument orientation, which measures apparent conductivity in the upper 3 m of the subsurface, measured values ranged from 7 to 528 millisiemens per meter (mS/m) and averaged 94 mS/m (table 1). A similar average (but lower maximum value) was obtained in the vertical dipole (VD) orientation, where the instrument explores to a depth of about 6 m (table 1).

We classified HD and VD apparent conductivities into five categories. HD values between 7 and 64 mS/m were considered low, 65 to 105 mS/m were low to moderate, 106 to 166 mS/m were moderate, 167 to 298 mS/m were moderate to high, and values of 299 mS/m and above were high (fig. 6). Slightly lower equivalent ranges were used for the VD measurements (fig. 7). Comparisons of the HD and VD values (appendix A) indicate they are highly correlated such that sites with high HD values also had high VD values. Despite the limited access to the river and its tributaries, we recorded elevated conductivities at several sites that are consistent with near-surface salinization that may contributed to degraded Colorado River water quality.

Lake Spence Area

Lake Spence is not part of TMDL segment 1426, but its relatively poor water quality is a strong control on water quality in the Colorado River downstream from the lake. We measured apparent ground conductivity along several tributaries adjacent to the lake, including the Colorado River (figs. 6 and 7).

Moderate to high apparent conductivities were recorded along Salt Creek at the Paint Creek Recreation Area (area A, figs. 6 and 7; locations C028 to C039, appendix A). An apparent conductivity profile along the stream (figs. 8 and 9) depicts elevated conductivities ranging from 122 to 192 mS/m in the shallower HD orientation and 71 to 116 mS/m in the deeper VD mode, suggesting surface salinization associated with evaporative concentration or the presence of contributing salinity sources farther upstream. Surface water at this location was moderately saline in August 2004 (fig. 5).

Table 1. Statistical parameters for apparent ground conductivity measurements acquired in July and August 2004 in the upper Colorado River area, Coke and Runnels counties, Texas (appendix A) using a Geonics EM31 instrument (fig. 3). Horizontal-dipole (HD) measurements represent the upper 3 m of the subsurface; vertical-dipole (VD) measurements represent the upper 6 m.

Instrument Orientation	Number	Average (mS/m)	Minimum (mS/m)	Maximum (mS/m)	Std. Dev. (mS/m)
Horizontal dipole	219	94	7	528	64
Vertical dipole	219	96	8	267	42



Figure 8. Photograph looking upstream along Salt Creek at Lake Spence.

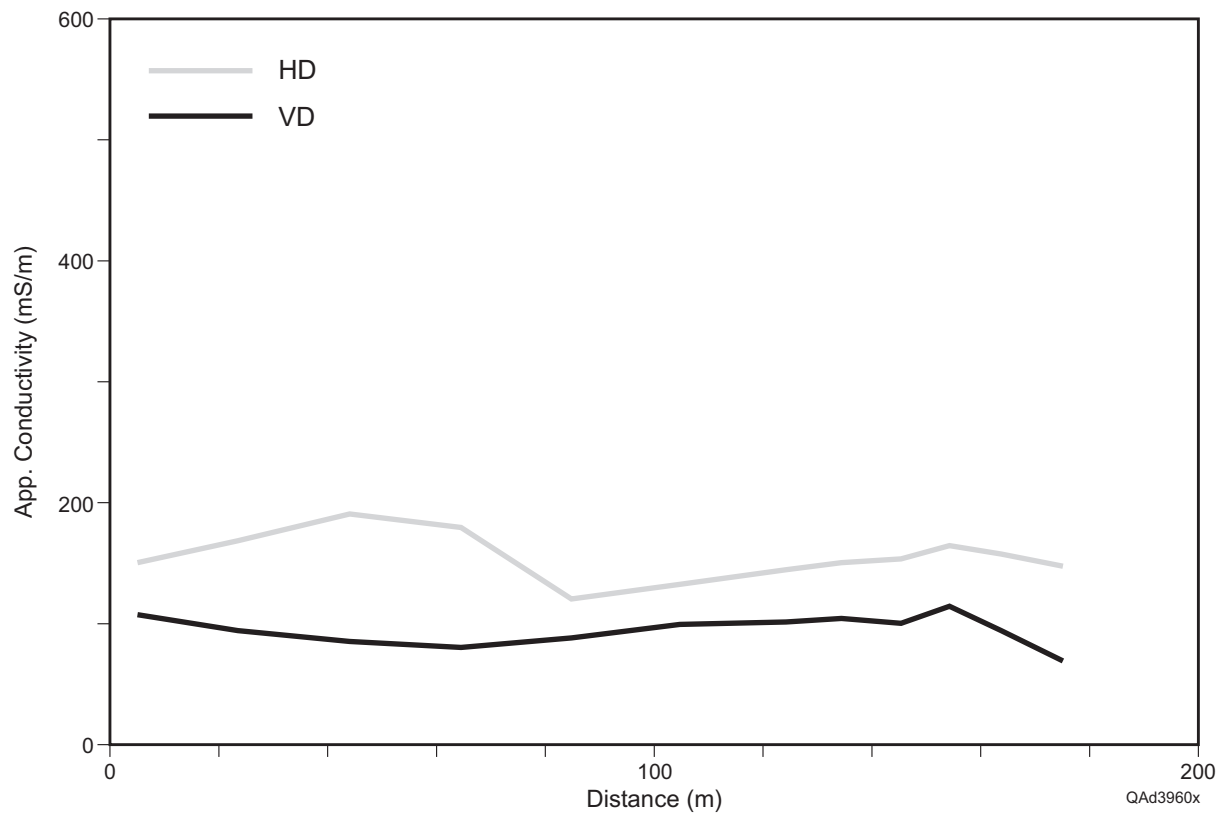


Figure 9. Apparent ground conductivity profile downstream along Salt Creek at Lake Spence.

The highest ground conductivities measured in the Lake Spence area were located along the Colorado River upstream from Lake Spence at the RR 2059 bridge (area B, figs. 6 and 7; locations C237 and C238, appendix A). These elevated conductivities coincided with efflorescence and dense growth of salt cedar on streambank alluvial deposits, but surface-water measurements at this site indicated fresh water flowing in the river. This area has undergone extensive historic hydrocarbon exploration and production that is a possible source for the observed ground salinization, as are other possible sources farther upstream.

Relatively low apparent conductivity was measured along most other tributaries surrounding Lake Spence (figs. 6 and 7), including Wildcat Creek (45 to 85 mS/m at locations C020 to C027, appendix A), Pecan Creek (40 to 54 mS/m at locations C042 to C045), Paint Creek (32 to 53 mS/m at locations C046 to C048), and Yellow Wolf Creek (30 to 58 mS/m at locations C053 to C054). Moderate conductivities (64 to 235 mS/m at locations C239 to C243) were measured along Rough Creek where it crosses an oil field on the north side of Lake Spence.

Colorado River Downstream from Lake Spence

With a few exceptions, apparent ground conductivity measured in the HD and VD orientations along 10 segments of the Colorado River downstream from Lake Spence are in the low to moderate categories (figs. 6 and 7; table 2) and are generally less than 100 mS/m. The first Colorado River segment below Lake Spence where anomalously high apparent conductivity was recorded was at a gravel quarry near the confluence with Machae Creek (area C, figs. 6 and 7). In addition to surface evidence of salinization that included efflorescence visible on alluvial deposits adjacent to the river (fig. 10), we measured apparent conductivities that increased from near-background levels of about 100 mS/m upstream from the apparent saline seep area to values as high as 528 mS/m in the shallower HD orientation and 267 mS/m in the deeper VD orientation (fig. 11). We also measured the highest Colorado River water salinity at this site (1520 mg/L at locations C190 and C191, appendix B).

Table 2. Apparent ground conductivity ranges in the HD and VD instrument orientations along the Colorado River, listed in downstream order. Individual locations and measurements are listed in appendix A and shown on figs. 6 and 7.

Colorado River Segment	Locations	VD mS/m	HD mS/m
Near RR 2059 bridge upstream from L. Spence	C237 to C238	170-180	200-298
Robert Lee	C055 to C064	64-108	48-119
Gravel quarry at Machae Creek	C077 to C089	126-267	95-528
Near U.S. 277 bridge (upstream)	C123 to C128	85-96	76-90
Near U.S. 277 bridge (downstream)	C110 to C111	88-90	78-110
Near Kickapoo Creek confluence	C117 to C121	69-128	115-131
Runnels County road crossing	C132 to C137	56-102	40-98
Near FM 3115 bridge	C150 to C159	62-86	65-88
Near FM 2111 bridge (downstream side)	C173 to C176	78-88	74-114
U.S. 67 and U.S. 83 bridges, Ballinger	C184 to C186	90-163	62-105
Runnels County Road 129 bridge	C207	56	46



Figure 10. Photograph of efflorescence on the bank of the Colorado River in a saltwater seep area near Machae Creek.

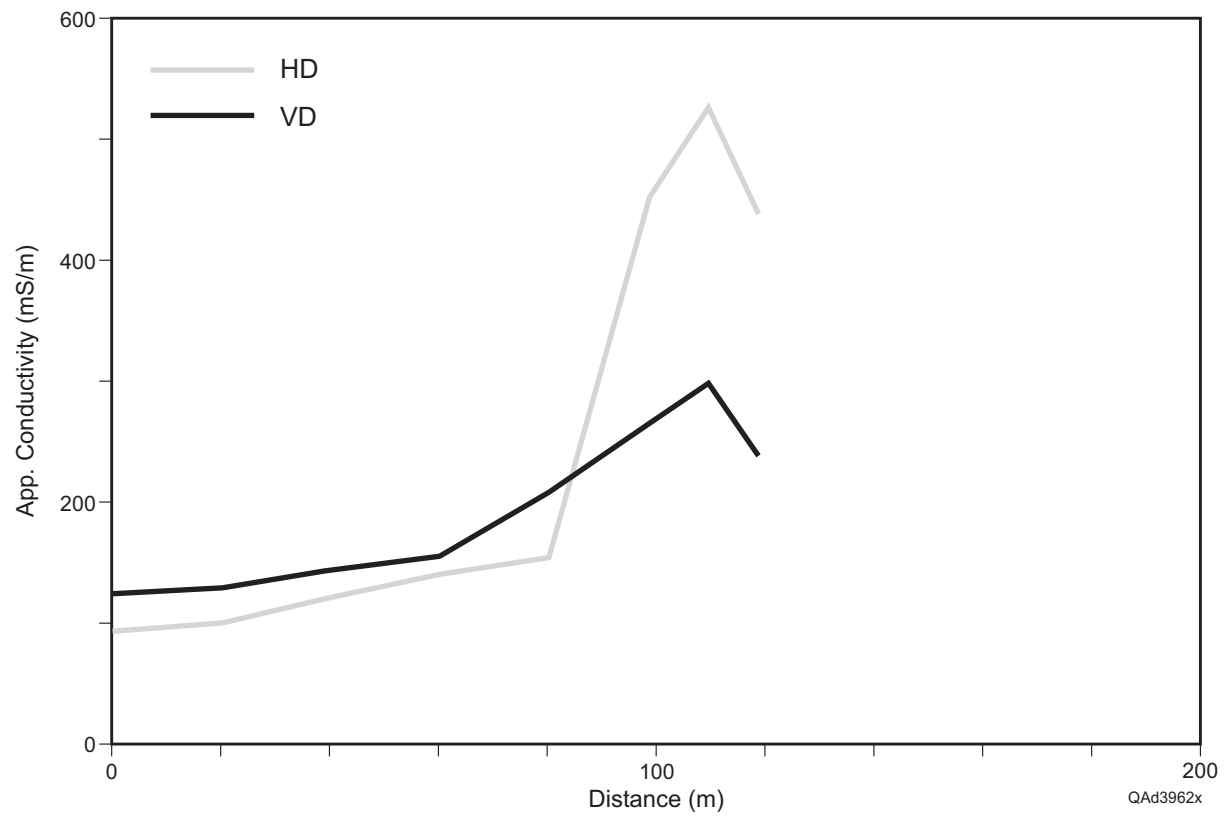


Figure 11. Apparent ground conductivity profile downstream along the Colorado River near Machae Creek.

Possible sources of salinity in this area include natural discharge of saline groundwater and nearby oilfield-related discharge.

Apparent conductivities in the low to moderate range were measured along the river at the U.S. 277 bridge south of Bronte (figs. 6 and 7; table 2). Slightly higher apparent conductivities, reaching 128 to 131 mS/m, were measured a short distance downstream near the Kickapoo Creek confluence (figs. 6 and 7; table 2).

Farther downstream, measured apparent conductivity remained mostly in the low to moderate ranges at county road and highway crossings where the river is accessible, such as FM 3115 and FM 2111 bridges between Bronte and Ballinger (figs. 6 and 7; table 2). A single moderately high conductivity was measured along the river beneath the U.S. 67 bridge at Ballinger (163 mS/m at location C186, appendix A) that may be affected by cultural noise and not imply a local increase in ground conductivity or salinity.

Apparent conductivities measured along the Colorado River at the Runnels County Road 129 bridge, the most downstream location visited, are 46 to 56 mS/m (area E, figs. 6 and 7; table 2), virtually the lowest values measured along the river. These values are consistent with low-TDS concentration measured in water samples at this site (location C206, appendix B), reflecting the significant addition of fresh water to the Colorado River at the Elm Creek confluence in Ballinger.

Colorado River Tributaries Below Lake Spence

We measured apparent conductivity at one or more locations along 27 tributaries on the north and south sides of the Colorado River below Lake Spence (figs. 6 and 7; table 3; appendix A) in an attempt to identify salinized tributaries that might contribute high-TDS water to the Colorado River. Most of the tributaries were not flowing during our survey, but we expect that apparent ground conductivity measured in dry stream beds will remain elevated if the stream carries saline water when it does flow. Low apparent ground conductivity is expected along relatively fresh creeks; high apparent conductivity should be measured along relatively saline creeks.

Table 3. Apparent ground conductivity ranges in the HD and VD instrument orientations along Colorado River tributaries on the north (N) and south (S) side of the river, listed in downstream order. Individual locations and measurements are listed in appendix A and shown on figs. 6 and 7.

Tributary Segment	Locations	VD mS/m	HD mS/m
Pecan Creek (S, Lake Spence)	C042 to C045	46-54	40-46
Rough Creek (N, Lake Spence)	C239 to C243	71-135	64-107
Yellow Wolf Creek (N, Lake Spence)	C053 to C054	47-58	30-39
Salt Creek (S, Lake Spence)	C028 to C041	71-109	67-192
Paint Creek (S, Lake Spence)	C046 to C048	46-53	32-39
Wildcat Creek (S, Lake Spence)	C020 to C027	59-85	45-61
Messbox Creek (N)	C013 to C018	65-121	75-100
Mountain Creek (N, Robert Lee)	C065 to C075	66-120	49-120
Jack Miles Creek (S)	C229 to C230	94-99	66-74
Machae Creek (N)	C091 to C101	73-205	62-224
Buffalo Creek (S)	C231 to C235	42-80	34-51
Turkey Creek (N)	C102 to C103	72-85	47-62
Double Barrel Creek (N)	C104 to C105	55-60	31-40
Live Oak Creek (S)	C225 to C227	25-30	20-24
Live Oak Creek tributary (S)	C223 to C224	34	26-30
Kickapoo Creek at U.S. 277 (N)	C106 to C109	73-83	54-63
Kickapoo Creek at Colorado River (N)	C112 to C116	99-137	78-211
Hog Creek (N)	C129 to C131	53-60	41-48
Oak Creek (N)	C138 to C149	101-126	89-124
Juniper Creek (S)	C220 to C222	63-88	65-95
Mule Creek (S)	C218 to C219	75-85	60-65
Antelope Creek (S)	C216 to C217	55-71	56-58
Red Bank Creek (S)	C214 to C215	98-111	103-129
Indian Creek (S)	C213	101	84
Quarry Creek (N)	C169 to C171	92-109	65-88
Valley Creek, upstream (N)	C160 to C164	99-125	75-116
Valley Creek, downstream (N)	C165 to C168	87-89	57-72
Rocky Creek (S)	C211 to C212	72-78	54-56
Los Arroyos (N)	C177 to C180	97-105	101-147
Elm Creek (N)	C181 to C183	55 to 64	41 to 50
Bears Foot Creek (N)	C199 to C200	85-93	78-97
Spur Creek (S)	C209 to C210	89-102	81-111
Mustang Creek (N)	C201 to C205	75-86	49-69

In downstream order on the north side of the Colorado, we acquired data along Messbox and Mountain creeks near Robert Lee, Machae, Turkey, and Double Barrel creeks between Robert Lee and Bronte, Kickapoo, Hog, Oak, Quarry, and Valley creeks and Los Arroyos between Bronte and Ballinger, and Elm, Bears Foot, and Mustang creeks below Ballinger (table 3; figs. 6 and 7). On the south side of the Colorado, we acquired data along Jack Miles, Buffalo, and Live Oak creeks between Robert Lee and Bronte, Juniper, Antelope, Red Bank, Indian, and Rocky Creek between Bronte and Ballinger, and Spur Creek downstream from Ballinger (table 3; figs. 6 and 7).

Out of the 16 creek segments on the north side of the Colorado, we recorded apparent ground conductivities above 100 mS/m along only seven (Messbox, Mountain, Machae, Kickapoo, Oak, and Valley creeks and Los Arroyos). The highest values were measured at Machae Creek (as great as 224 mS/m in the HD orientation and 205 mS/m in the VD orientation near area C, figs. 6 and 7; table 3) at locations near its confluence with the Colorado River where high TDS values were measured in water samples, efflorescence was observed on the ground adjacent to the river, and elevated ground conductivities were measured. This is an area where oilfield activities continue and represent a possible salinity source.

The only other northern tributary where anomalously high apparent conductivities were measured was the downstream end of Kickapoo Creek near Bronte (figs. 6 and 7), where highest measured values reached 211 mS/m in the HD orientation and 137 mS/m in the VD orientation. These values are somewhat higher than those measured along the Colorado River in this area, suggesting possible minor salinity sources along Kickapoo Creek, probably downstream from Bronte.

A short segment along the dry stream bed of Mountain Creek near Robert Lee also exceeded 100 mS/m (fig. 12). Relatively low peaks such as these that extend only a short distance along a stream bed are unlikely to represent major salinity sources.

Apparent ground conductivity exceeded 100 mS/m at only two creeks on the south side of the Colorado. Peak values reached 129 mS/m on Red Bank Creek and 111 mS/m on Spur Creek (figs. 6 and 7; table 3). Conductivities measured at all remaining measured creek segments on the north and south sides of the Colorado were below 100 mS/m, suggesting that major salinity sources are unlikely to

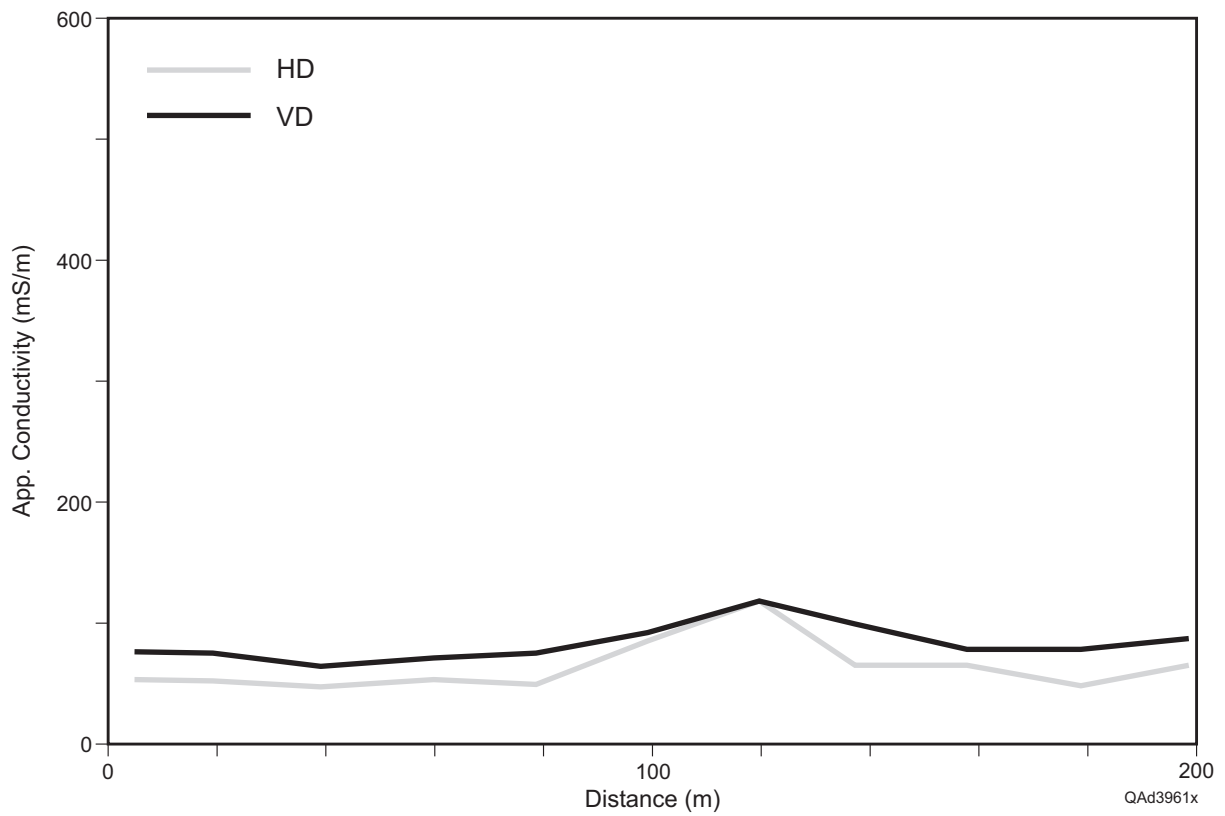


Figure 12. Apparent ground conductivity profile downstream along Mountain Creek (dry) at Robert Lee.

exist upstream from the measurement points on these tributaries. Significant sources affecting Colorado River salinity may exist between the Colorado River and the most downstream measurement location on each tributary, as well as along segments of the Colorado River and its tributaries that were inaccessible by foot, vehicle, or canoe during the field survey.

AIRBORNE GEOPHYSICAL SURVEY RECOMMENDATIONS

Limited access to the Colorado River and its tributaries by foot, public road, or watercraft precludes a comprehensive assessment of potentially salinized segments of the river below Lake Spence. Where there was access to the river, local areas of elevated conductivity and relatively high TDS water were identified, such as the area near Machae Creek downstream from Robert Lee. In addition, the presence of relatively high salinity water in Lake Spence and likely natural and oilfield sources of salinity upstream from Lake Spence, including along significant tributaries such as Beals Creek (Sullivan and others, 1999) suggests that the most efficient next step would be to conduct a reconnaissance airborne geophysical survey of the area. Rather than fly a gridded survey over the entire area of interest that would be prohibitively expensive, we recommend an innovative approach in which a low-flying helicopter would carry a multi-frequency EM conductivity meter along the axis of the Colorado River along the entire length of segment 1426. Because there are significant salinity sources upstream from Lake Spence that impact Colorado River water quality in segment 1426, the river-axis survey could be extended farther upstream to Lake Thomas and along Beals Creek from near Big Spring to its confluence with the Colorado River (fig. 13).

Products from such a survey would include conductivity profiles along the entire river segment depicting conductivity changes with depth, allowing users to identify the extent and intensity of salinized areas that are likely contributors to poor Colorado River water quality in segment 1426.

Total Colorado River and Beals Creek flying distance is estimated to be 434 km, including 336 km along the Colorado River from Lake Thomas to the southeast corner of Runnels County and 98 km along Beals Creek upstream from its confluence with the Colorado River. In addition, 200 flight km

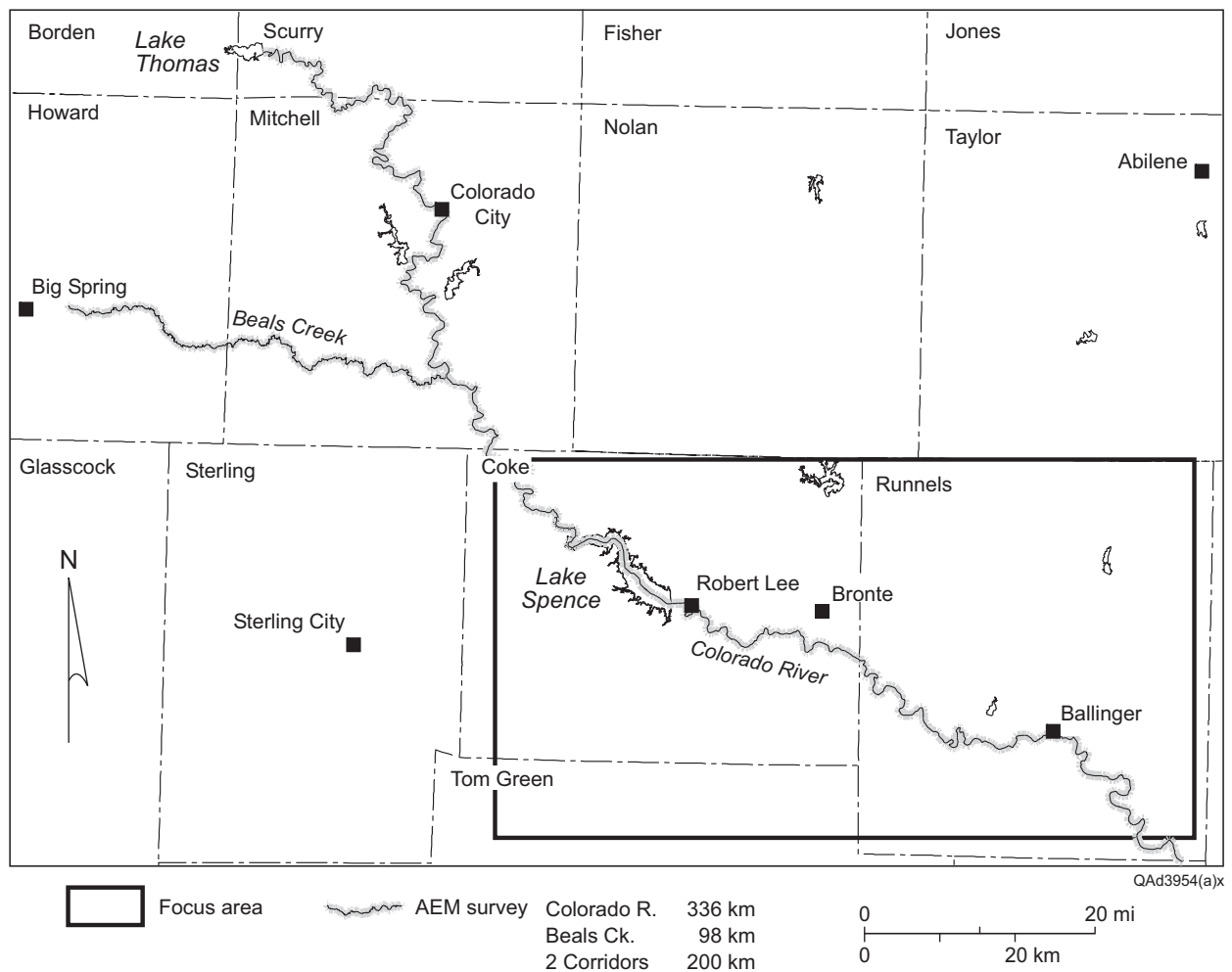


Figure 13. Recommended airborne geophysical survey route along the axis of the Colorado River from Lake Thomas to below Ballinger and along Beals Creek from Big Spring to the Colorado River confluence.

should be set aside for two gridded airborne geophysical surveys along segment 1426, with specific locations to be chosen during the airborne survey based on measured water salinities (fig. 14), ground-based conductivity measurements (fig. 15), and daily in-the-field results from the airborne survey of the river axis. These two corridors should be placed where significant salinization has been identified along the river.

CONCLUSIONS

We supplemented existing water-quality data on Colorado River segment 1426 with additional measurements of surface water conductivity and salinity and shallow ground conductivity measurements around Lake Spence, along the Colorado River from Lake Spence to below Ballinger, and along numerous Colorado River tributaries north and south of the river. Water samples verified the presence of saline water in Lake Spence and its Salt Creek tributary, as well as elevated salinities in the Colorado River from Lake Spence to Ballinger. At Ballinger, significant fresh inflow from Elm Creek reduced Colorado River salinity to below 1000 mg/L TDS concentration.

Measured ground conductivity was low to moderate across most of the study area. Elevated ground conductivities indicating local natural or oilfield salinization were measured along Salt Creek and the Colorado River flowing into Lake Spence, near the confluence of the Colorado River and Machae Creek downstream from Robert Lee, and near the confluence of the Colorado River and Kickapoo Creek near Bronte. Most of the tributaries were not flowing during the survey, but showed little evidence of significant salinity contributions to the Colorado River. Low measured ground conductivity along the river and its tributaries below Ballinger is consistent with low TDS samples from the area.

Limited ground access to the Colorado River combined with evidence for river salinity sources both within and upstream from segment 1426 suggest that a more comprehensive analysis of river salinization should include a reconnaissance airborne geophysical survey to measure the electrical conductivity along the axis of the Colorado River to multiple exploration depths along the entire length of segment 1426, upstream from Lake Spence along the Colorado River to Lake Thomas, and along

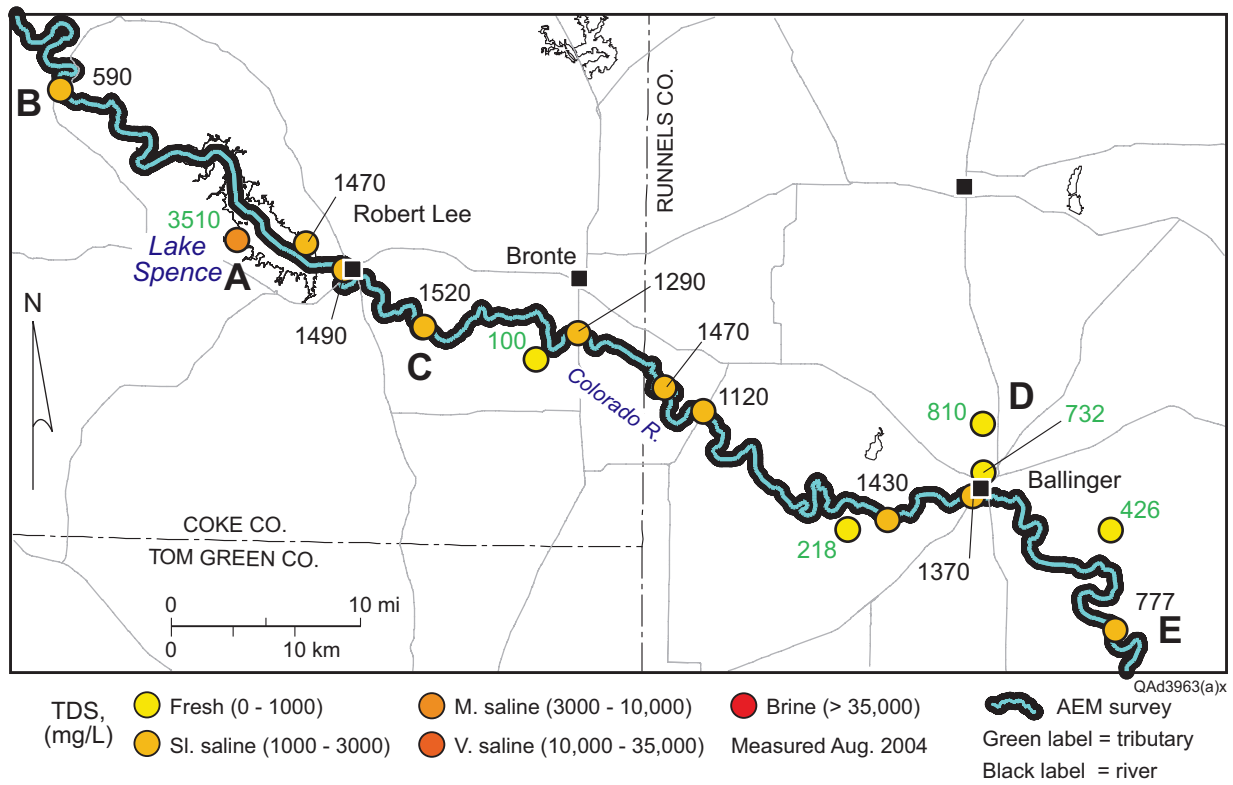


Figure 14. August 2004 TDS concentrations superimposed on part of the recommended airborne geophysical survey route along TMDL segment 1426.

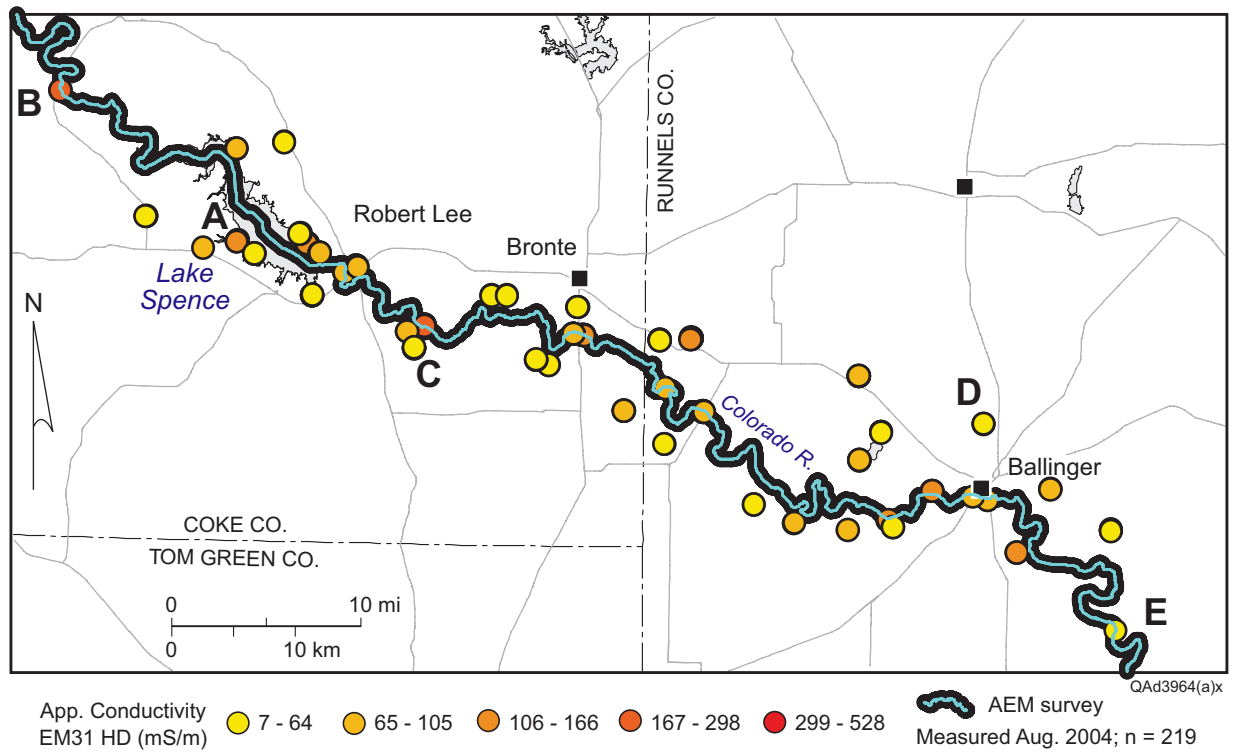


Figure 15. Apparent ground conductivity measurements superimposed on part of the recommended airborne geophysical survey route along TMDL segment 1426.

Beals Creek. In addition, two small, gridded airborne surveys are recommended for the 1426 segment to characterize demonstrated salinized areas in more detail. The locations of these areas should be chosen in the field during the airborne survey of the river axis.

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APPENDIX A: APPARENT GROUND CONDUCTIVITY MEASUREMENTS

Apparent conductivity measured in the upper Colorado River area, July and August 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
C003	31.91093	-100.52301	93	80	Lake Spence; Lakeview Recreation Area
C004	31.91091	-100.52313	90	74	“
C005	31.91091	-100.52325	89	80	“
C006	31.91091	-100.52334	83	93	“
C007	31.91089	-100.52341	107	105	“
C008	31.91088	-100.52355	121	115	“
C009	31.91084	-100.52363	122	123	“
C010	31.91083	-100.52374	115	118	“
C011	31.91083	-100.52388	127	133	“
C012	31.91086	-100.52397	112	140	“
C013	31.90407	-100.51304	82	80	Messbox Creek
C014	31.90417	-100.51302	65	75	“
C015	31.90425	-100.51298	90	77	“
C016	31.90434	-100.51292	98	90	“
C017	31.90444	-100.51289	118	89	“
C018	31.90449	-100.51281	121	100	“
C020	31.87333	-100.51915	85	61	Wildcat Creek
C021	31.87340	-100.51908	68	51	“
C022	31.87344	-100.51898	59	49	“
C023	31.87352	-100.51892	65	45	“
C024	31.87359	-100.51886	70	55	“
C025	31.87364	-100.51876	64	61	“
C026	31.87369	-100.51868	67	60	“
C027	31.87376	-100.51859	61	51	“
C028	31.91257	-100.58280	71	149	Salt Creek
C029	31.91249	-100.58288	96	159	“
C030	31.91241	-100.58292	116	166	“
C031	31.91233	-100.58297	102	155	“
C032	31.91227	-100.58306	106	152	“
C033	31.91219	-100.58311	103	146	“
C034	31.91207	-100.58326	101	134	“
C035	31.91193	-100.58341	90	122	“
C036	31.91182	-100.58358	82	181	“
C037	31.91172	-100.58376	87	192	“
C038	31.91158	-100.58391	96	170	“
C039	31.91144	-100.58403	109	152	“
C041	31.90674	-100.61230	71	67	Salt Creek; Dripping Springs
C042	31.92918	-100.66157	54	46	Pecan Creek
C043	31.92912	-100.66166	48	40	“
C044	31.92909	-100.66176	46	43	“

C045	31.92905	-100.66188	48	44	“
C046	31.90317	-100.56874	53	39	Paint Creek
C047	31.90325	-100.56876	47	32	“
C048	31.90334	-100.56873	46	36	“
C049	31.91828	-100.52989	8	8	Lake Spence; Lakeview Recreation Area
C050	31.91822	-100.53010	9	8	“
C051	31.91814	-100.53028	8	7	“
C052	31.91804	-100.53046	8	7	“
C053	31.98457	-100.54439	47	30	Yellow Wolf Creek
C054	31.98453	-100.54445	58	39	“
C055	31.89191	-100.49170	87	59	Colorado River; Robert Lee
C056	31.89173	-100.49165	66	50	“
C057	31.89155	-100.49170	84	112	“
C058	31.89137	-100.49176	83	119	“
C059	31.89119	-100.49173	93	104	“
C060	31.89101	-100.49181	108	109	“
C061	31.89084	-100.49184	102	61	“
C062	31.89067	-100.49189	96	74	“
C063	31.89048	-100.49185	76	48	“
C064	31.89026	-100.49191	64	75	“
C065	31.89554	-100.48186	78	55	Mountain Creek; Robert Lee
C066	31.89544	-100.48169	77	54	“
C067	31.89527	-100.48160	66	49	“
C068	31.89511	-100.48148	73	55	“
C069	31.89495	-100.48139	77	51	“
C070	31.89481	-100.48126	94	87	“
C071	31.89464	-100.48115	120	120	“
C072	31.89455	-100.48099	101	67	“
C073	31.89449	-100.48073	80	67	“
C074	31.89442	-100.48049	80	50	“
C075	31.89432	-100.48033	89	67	“
C077	31.85091	-100.42461	126	95	Colorado River; gravel quarry
C078	31.85089	-100.42441	131	102	“
C079	31.85089	-100.42420	145	122	“
C080	31.85095	-100.42398	157	142	“
C081	31.85097	-100.42377	210	156	“
C082	31.85109	-100.42359	267	454	Colorado River; gravel quarry; efflorescence
C083	31.85114	-100.42349	176	528	“
C084	31.85115	-100.42339	200	440	“
C085	31.85095	-100.42355	252	212	Colorado River; gravel quarry
C086	31.85096	-100.42345	264	210	“
C087	31.85093	-100.42336	217	177	“
C088	31.85092	-100.42325	247	192	“
C089	31.85077	-100.42306	199	155	“
C091	31.85333	-100.42340	131	80	Machae Creek
C092	31.85323	-100.42322	155	127	“
C093	31.85303	-100.42318	205	151	“
C094	31.85290	-100.42302	189	144	“
C095	31.85273	-100.42296	205	153	“
C096	31.85265	-100.42304	198	223	“
C097	31.85251	-100.42299	171	224	“
C098	31.85249	-100.42288	190	170	“
C099	31.85353	-100.42349	113	88	“

C100	31.85366	-100.42364	97	77	“
C101	31.85374	-100.42378	73	62	“
C102	31.87520	-100.36633	85	62	Turkey Creek
C103	31.87495	-100.36625	72	47	“
C104	31.87521	-100.35274	55	31	Double Barrel Creek
C105	31.87506	-100.35288	60	40	“
C106	31.86697	-100.29258	73	54	Kickapoo Creek at U.S. 277
C107	31.86701	-100.29279	78	54	“
C108	31.86707	-100.29287	79	63	“
C109	31.86714	-100.29297	83	58	“
C110	31.84702	-100.28923	90	78	Colorado River; U.S. 277 to Kickapoo Creek
C111	31.84709	-100.28920	88	100	“
C112	31.84697	-100.28788	115	211	Kickapoo Creek; mouth
C113	31.84700	-100.28811	137	120	“
C114	31.84667	-100.28677	99	46	“
C115	31.84716	-100.28682	108	130	Kickapoo Creek
C116	31.84710	-100.28683	136	97	“
C117	31.84679	-100.28734	69	120	Colorado River; near Kickapoo Creek confluence
C118	31.84684	-100.28718	128	115	“
C119	31.84679	-100.28714	121	131	“
C120	31.84670	-100.28703	118	116	“
C121	31.84668	-100.28692	101	129	“
C123	31.84791	-100.29660	109	80	Colorado River; upstream from U.S. 277
C124	31.84792	-100.29650	91	76	“
C125	31.84792	-100.29639	88	78	“
C126	31.84789	-100.29628	96	85	“
C127	31.84789	-100.29617	90	90	“
C128	31.84789	-100.29606	85	85	“
C129	31.84437	-100.22253	60	42	Hog Creek
C130	31.84418	-100.22266	53	41	“
C131	31.84406	-100.22276	57	48	“
C132	31.84392	-100.22290	56	40	“
C133	31.80920	-100.21784	102	98	Colorado River; county road crossing
C134	31.80934	-100.21771	88	79	“
C135	31.80937	-100.21767	92	82	“
C136	31.80937	-100.21755	88	82	“
C137	31.80941	-100.21738	96	94	“
C138	31.84610	-100.19607	107	89	Oak Creek
C139	31.84600	-100.19590	106	92	“
C140	31.84588	-100.19573	101	89	“
C141	31.84577	-100.19557	106	95	“
C142	31.84561	-100.19545	113	115	“
C143	31.84543	-100.19542	114	129	“
C144	31.84526	-100.19548	114	118	Oak Creek; at seep
C145	31.84507	-100.19554	126	124	Oak Creek
C146	31.84491	-100.19573	100	124	“
C147	31.84479	-100.19589	106	95	“
C148	31.84472	-100.19615	102	103	“
C149	31.84464	-100.19638	114	122	“
C150	31.79261	-100.18478	80	93	Colorado River; upstream from FM 3115 bridge
C151	31.79271	-100.18545	83	71	“

C152	31.79266	-100.18532	73	65	“
C153	31.79268	-100.18523	79	77	“
C154	31.79267	-100.18513	81	71	“
C155	31.79267	-100.18502	81	68	“
C156	31.79263	-100.18493	86	81	“
C157	31.79236	-100.18434	62	79	Colorado River; downstream from FM 3115 bridge
C158	31.79234	-100.18426	65	78	“
C159	31.79231	-100.18417	72	88	“
C160	31.81908	-100.05254	99	75	Valley Creek
C161	31.81926	-100.05264	110	78	“
C162	31.81942	-100.05273	113	116	“
C163	31.81959	-100.05277	114	112	“
C164	31.81977	-100.05283	125	105	“
C165	31.77918	-100.03287	88	63	“
C166	31.77900	-100.03284	87	72	“
C167	31.77883	-100.03289	89	66	“
C168	31.77864	-100.03293	88	57	“
C169	31.75831	-100.05142	106	88	Quarry Creek
C170	31.75847	-100.05156	109	85	“
C171	31.75853	-100.05175	92	65	“
C173	31.71485	-100.02673	86	74	Colorado River; downstream from FM 2111 bridge
C174	31.71486	-100.02673	78	76	“
C175	31.71484	-100.02666	88	101	“
C176	31.71494	-100.02651	86	114	“
C177	31.73634	-99.98963	97	147	Los Arroyos
C178	31.73635	-99.98944	105	112	“
C179	31.73635	-99.98921	98	101	“
C180	31.73653	-99.98903	104	115	“
C181	31.78535	-99.94610	55	50	Elm Creek
C182	31.78547	-99.94595	64	41	“
C183	31.78559	-99.94579	62	45	“
C184	31.73000	-99.94186	90	62	Colorado River; U.S. 83 bridge
C185	31.73004	-99.94210	90	68	“
C186	31.73258	-99.95472	163	105	Colorado River; U.S. 67 bridge
C199	31.73876	-99.88884	85	78	Bears Foot Creek; County Road 122
C200	31.73860	-99.88874	93	97	“
C201	31.70955	-99.83671	83	60	Mustang Creek at county road
C202	31.70941	-99.83673	70	49	“
C203	31.70905	-99.83675	86	69	“
C204	31.70879	-99.83680	75	60	“
C205	31.70856	-99.83681	75	53	“
C207	31.63603	-99.83225	56	46	Colorado River; County Road 129
C209	31.69229	-99.91707	89	81	Spur Creek; County Road 114
C210	31.69237	-99.91681	102	111	“
C211	31.71016	-100.02246	72	56	Rocky Creek; County Road 287
C212	31.71011	-100.02256	78	54	“
C213	31.70768	-100.06100	101	84	Indian Creek; County Road 287
C214	31.71207	-100.10652	111	129	Red Bank Creek
C215	31.71233	-100.10643	98	103	“
C216	31.72561	-100.14081	71	56	Antelope Creek
C217	31.72539	-100.14096	55	58	“
C218	31.76844	-100.21734	85	65	Mule Creek

C219	31.76839	-100.21769	75	60	“
C220	31.79256	-100.25263	63	65	Juniper Creek
C221	31.79248	-100.25251	87	76	“
C222	31.79243	-100.25244	88	95	“
C223	31.82520	-100.31650	34	26	Live Oak Creek tributary
C224	31.82504	-100.31648	34	30	“
C225	31.82854	-100.32744	25	24	Live Oak Creek
C226	31.82865	-100.32747	30	22	“
C227	31.82889	-100.32743	28	20	“
C229	31.84775	-100.43790	94	66	Jack Miles Creek
C230	31.84783	-100.43791	99	74	“
C231	31.83588	-100.43149	80	38	Buffalo Creek
C232	31.83607	-100.43146	50	34	“
C233	31.83615	-100.43152	42	37	“
C234	31.83631	-100.43151	48	46	“
C235	31.83649	-100.43153	74	51	“
C237	32.01964	-100.73653	170	200	Colorado River; RR 2059 bridge
C238	32.01964	-100.73627	180	298	“
C239	31.97891	-100.58553	71	64	Rough Creek
C240	31.97896	-100.58539	84	79	“
C241	31.97906	-100.58527	95	84	“
C242	31.97919	-100.58524	135	107	“
C243	31.97929	-100.58512	127	98	“

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APPENDIX B: SURFACE WATER TEMPERATURE, CONDUCTIVITY, AND SALINITY

Temperature, apparent conductivity, and calculated total dissolved solids (TDS) concentration measured in surface-water samples from the upper Colorado River area, August 2-3, 2004. Values were measured using a Corning Checkmate 90 Conductivity and TDS Probe. Location coordinates, determined using a GPS receiver, are in decimal degrees using the 1984 World Geodetic System (WGS 1984).

Location	Latitude (degrees)	Longitude (degrees)	Temp. (deg. C)	App. Con. (mS/m)	TDS (mg/L)	Flow	Notes
C236	32.01974	-100.73617	33.2	118	590	flowing	Colorado River; RR 2059 bridge
C188	31.91212	-100.58331	37.3	702	3510	ponded	Salt Creek
C187	31.91060	-100.52474	32.2	295	1470	ponded	Lake Spence; Lakeview Recreation Area
C189	31.89188	-100.49169	35.4	298	1490	flowing	Colorado River; Robert Lee
C190	31.85075	-100.42468	31.9	305	1520	flowing	Colorado River; gravel quarry; upstream from efflorescence
C191	31.85092	-100.42321	32.0	307	1520	flowing	Colorado River; gravel quarry; downstream from efflorescence
C228	31.82847	-100.32753	37.2	19.9	100	ponded	Live Oak Creek
C192	31.84788	-100.29204	34.6	259	1290	flowing	Colorado River; U.S. 277 bridge
C193	31.80924	-100.21784	35.1	295	1470	flowing	Colorado River; county road crossing
C194	31.79256	-100.18473	34.2	225	1120	flowing	Colorado River; FM 3115 bridge
C213	31.70768	-100.06100	30.7	43.9	218	ponded	Indian Creek; County Road 287
C195	31.71484	-100.02668	34.7	285	1430	flowing	Colorado River; downstream from FM 2111 bridge
C198	31.73241	-99.95474	29.5	259	1370	flowing	Colorado River; U.S. 67 bridge
C196	31.78535	-99.94621	34.5	151	810	flowing	Elm Creek at county road
C197	31.74993	-99.94532	31.3	146	732	flowing	Elm Creek at Ballinger City Park
C203	31.70905	-99.83675	28.2	84.1	426	ponded	Mustang Creek at county road
C206	31.63588	-99.83225	31.9	156	777	flowing	Colorado River; County Road 129