RECONNAISSANCE GEOPHYSICAL INVESTIGATIONS OF SALINIZATION ALONG THE UPPER COLORADO RIVER ABOVE LAKE SPENCE, BORDEN, SCURRY, HOWARD, AND MITCHELL COUNTIES, TEXAS

by

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INTRODUCTION

This interim report summarizes additional reconnaissance investigations of surface-water salinity and shallow ground conductivity that were conducted in October 2004 along the upper Colorado River above E. V. Spence Reservoir (Lake Spence). These investigations, which supplemented similar work completed in July and August 2004 along TMDL segment 1426 below Lake Spence (Paine and Collins, 2004), were conducted to determine whether the recommended airborne geophysical survey of segment 1426 should be extended farther upstream to identify additional salinity sources that would degrade Colorado River water quality. Surface-water monitoring has revealed periodic and repeated high salinity values at several monitoring sites along segment 1426, 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).

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. 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, 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 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.

During our supplemental work described in this report, we acquired ground conductivity measurements at an additional 46 sites along the upper Colorado River, Beals Creek and other significant tributaries, and around Lake Spence and Lake Thomas on October 26 to 28, 2004 (appendix A). We acquired measurements 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 VD orientation; (2) noting the apparent conductivity reading; (3) rotating the instrument into the HD orientation; (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.

Water Conductivity and TDS

We measured the electrical conductivity of water samples at an additional 28 locations along the upper Colorado River, along Beals Creek and other significant tributaries, and at lakes (appendix B) using a Corning Checkmate 90 conductivity and TDS probe. All measurements were taken on Octo-

ber 26 to 28, 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.

SURFACE-WATER MEASUREMENTS

Total dissolved solids concentration in surface-water samples from the Colorado River and its lakes and tributaries is highly variable (fig. 1; appendix B). Concentrations range from fresh (100 mg/L) to very saline (more than 10,000 mg/L), averaging about 1900 mg/L for all samples.

October 2004 samples show that Colorado River salinity is more variable from one location to another between Lake Thomas and Lake Spence than it is along segment 1426 (Paine and Collins, 2004). At the most upstream location measured, the Colorado River had a TDS concentration of 1500 mg/L at the FM 1205 bridge above Lake Thomas (location C246, fig. 1; appendix B). Lake Thomas water was fresh (about 315 mg/L, locations C248 and C249); farther downstream, Lake Spence water was slightly saline (1330 mg/L, location C279). Between these reservoirs, Colorado River salinity ranged from 1540 (location C280 at RR 2059 above Lake Spence) to 6030 mg/L (location C302 at the I-20 bridge near Colorado City). Notable salinity increases occurred over relatively short distances along the river. Colorado River salinity increased from the Cedar Bend bridge (2390 mg/L at C305) to the highest measured river values at the I-20 bridge only 12 km downstream (6030 mg/L at C302).

The highest October 2004 salinities were measured along Beals Creek, a significant Colorado River tributary (fig. 1; appendix B). Near the upper end of the creek at the FM 700 bridge in Big Spring, salinity exceeded the upper limit of the instrument at more than 10,000 mg/L (location C305). There was a general downstream decrease in salinity along Beals Creek: 8160 mg/L at Midway Road (C285), 4550 mg/L at Moss Lake Road (C288), 5040 mg/L at FM 821 (C291), and 1690 mg/L at Texas 163 (C276). Salinities in other Colorado tributaries (in downstream order) include 1670 mg/L at

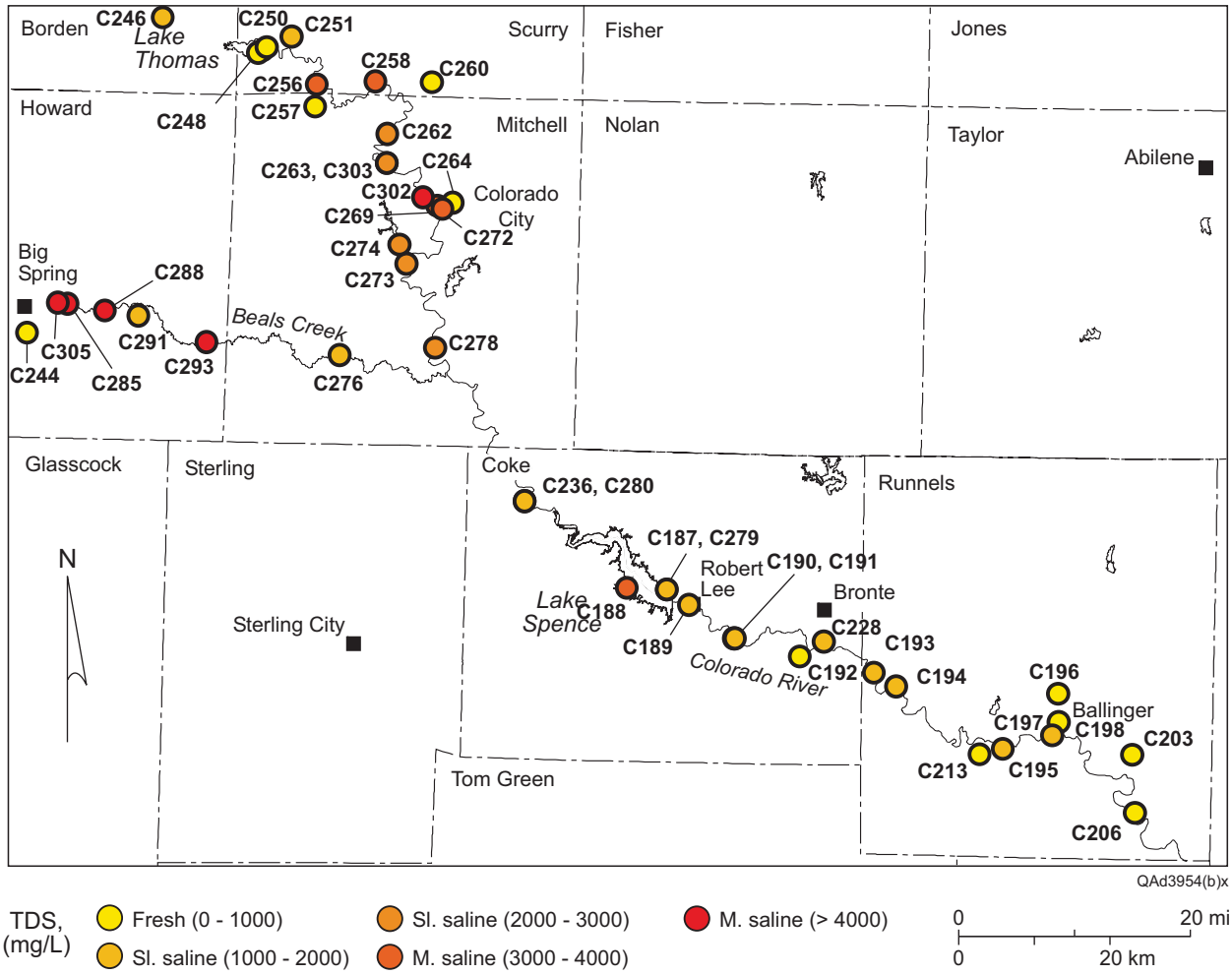

Figure 1. Map of the upper Colorado River region, West Texas (including TMDL segment 1426 below Lake Spence), depicting TDS concentrations measured in the Colorado River and its tributaries in August and October 2004. Symbol labels indicate measurement locations listed in appendix B. Salinity classification from Robinove and others (1958).

FM 2085 on Bull Creek (C251), 284 mg/L on ponded Willow Creek at FM 1229 (C257), 415 mg/L on Deep Creek at Scurry County Road 4138 (C260), 807 mg/L on Lone Wolf Creek at Colorado City (C264), and 2870 mg/L on ponded Morgan Creek at Texas 163 (C273).

GROUND-CONDUCTIVITY MEASUREMENTS

The additional 46 ground-conductivity measurements along the Colorado River and its tributaries above Lake Spence (figs. 2 and 3; appendix A) show that the shallow subsurface is generally more conductive above Lake Spence than it is below the lake. In the vertical dipole (VD) mode, which estimates apparent conductivity in the upper 6 m, conductivity above Lake Spence averages 167 mS/m (table 1) compared to 96 mS/m below Lake Spence (Paine and Collins, 2004). In the shallower horizontal dipole (HD) mode, which estimates apparent conductivity in the upper 3 m, conductivity above Lake Spence averages 171 mS/m compared to 94 mS/m below Lake Spence. These measurements are consistent with generally higher surface-water salinities in the same area.

Colorado River, Lake Thomas to Lake Spence

Ground-conductivity measurements taken in both instrument orientations along the Colorado River are consistently higher between Lake Thomas and Lake Spence than they are between Lake Spence and the most downstream point below Ballinger (figs. 2 and 3; table 2). Measurements along the Colorado River betwen Lake Spence and Lake Thomas range from 121 to 425 mS/m in the deeper (VD) mode and 137 to 376 mS/m in the shallower (HD) mode. Highest values were measured at the Texas 350 bridge in Scurry County (425 mS/m at location C255), near the I-20 and State Spur 377 bridges at Colorado City (as high as 376 mS/m at C298 to C301 and C269 to C271), and at the RR 2059 bridge upstream from Lake Spence (298 mS/m at C237 to C238). We measured slightly lower conductivity values upstream from Lake Thomas (47 to 154 mS/m at C245 and C246), just below Lake Thomas at the FM 1298 bridge (121 to 153 mS/m at C250), and below Colorado City at the Texas 163 and Mitchell County Road 337 bridges (123 to 139 mS/m at C272 and C278).

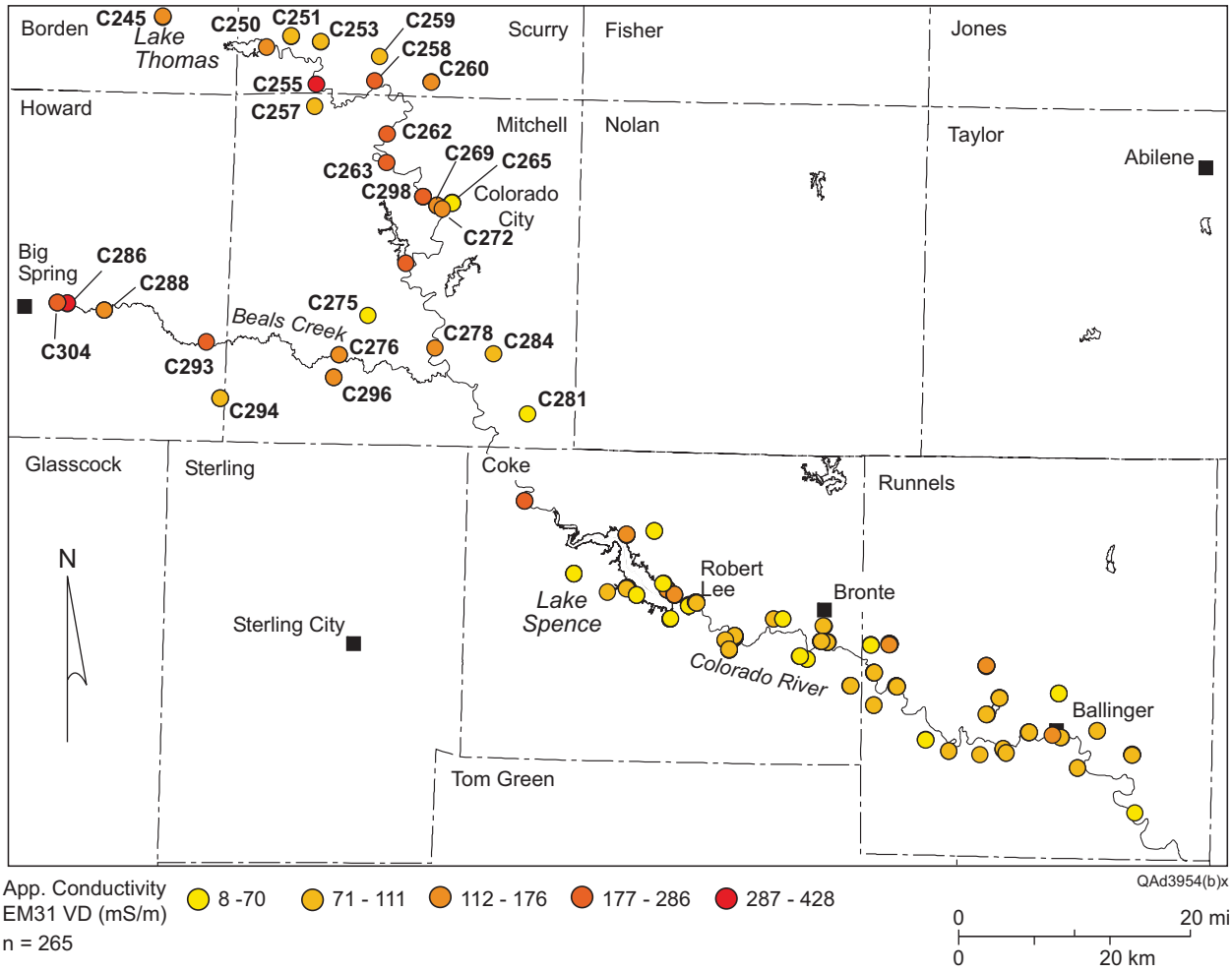

Figure 2. Apparent ground conductivity measured using an EM31 in the vertical dipole (VD) mode. Symbol labels indicate measurement locations listed in appendix A.

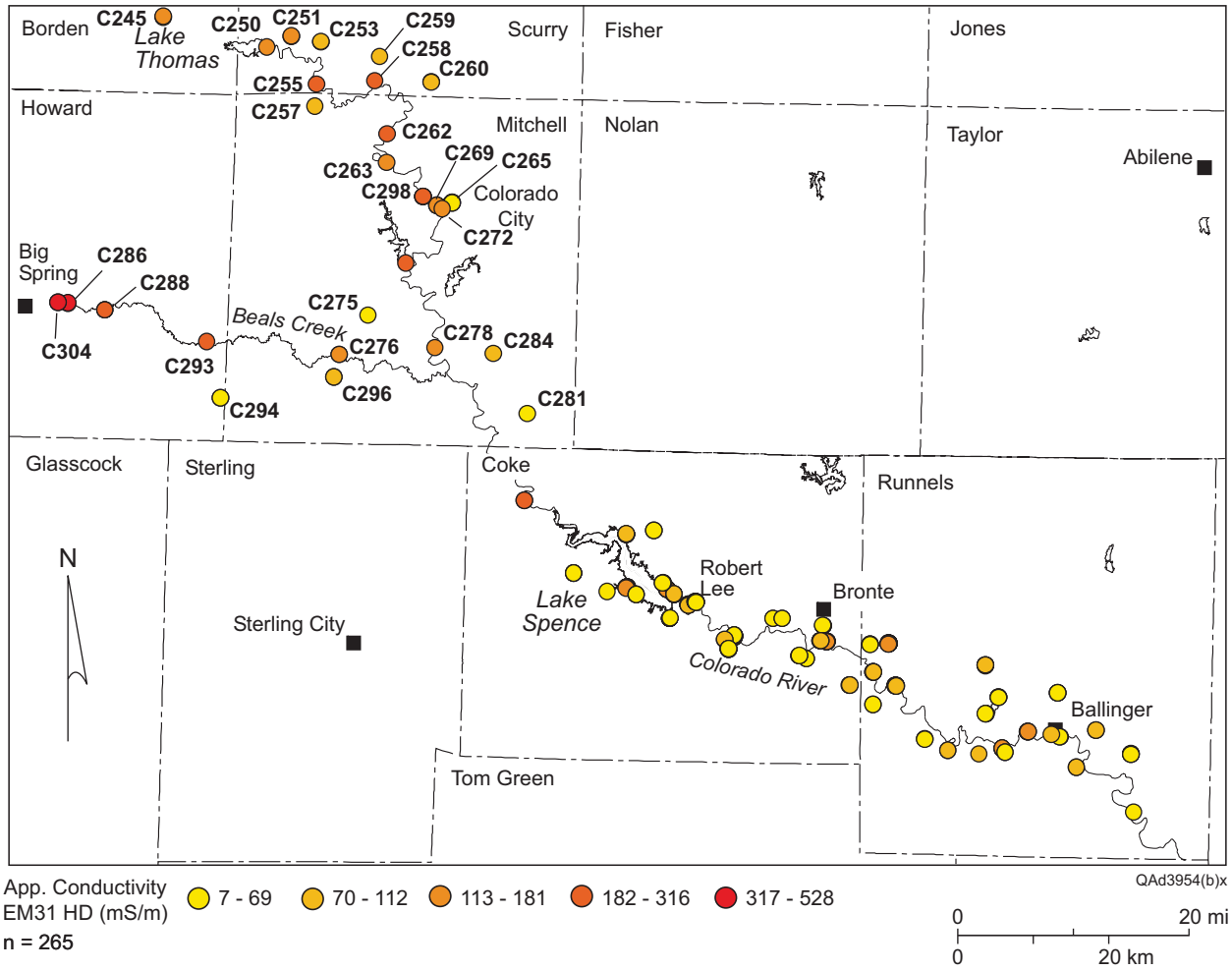

Figure 3. Apparent ground conductivity measured using an EM31 in the horizontal dipole (HD) mode. Symbol labels indicate measurement locations listed in appendix A.

Table 1. Statistical parameters for apparent ground conductivity measurements acquired in October 2004 in the upper Colorado River area, Borden, Scurry, Howard, and Mitchell counties, Texas (figs. 2 and 3; appendix A) using a Geonics EM31. 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)
HD	46	171	45	474	105
VD	46	167	56	428	90

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. 2 and 3.

Colorado River Segment	Locations	VD mS/m	HD mS/m
Near FM 1205 bridge upstream from L. Thomas	C245 to C246	56-146	47-154
Near FM 1298 bridge downstream from L. Thomas	C250	121	153
Near Texas 350 bridge	C255	425	275
Near FM 2835 bridge	C258	246	203
Near FM 1808 bridge	C262	220	260
Near Mitchell Co. Road 167	C263	207	155
Near I-20 bridge at Colorado City	C298 to C301	204-265	238-376
Near State Spur 377 bridge, Colorado City	C269 to C271	154-286	158-186
Near Texas 163 bridge, Colorado City	C272	124	137
Near Mitchell Co. Road 337	C278	123	139
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

Colorado River Tributaries, Lake Thomas to Lake Spence

We measured ground conductivity at 30 locations along 13 tributaries to the Colorado River between Lake Thomas and Lake Spence (figs. 2 and 3; table 3; appendix A). Ground conductivities along these tributaries range from 61 to 474 mS/m, generally higher than conductivities measured along most Colorado tributaries below Lake Spence.

The highest conductivities were measured at several locations along Beals Creek, which also contributed the highest surface-water salinity concentrations. Beals Creek ground conductivities near Big Spring ranged from 214 to 397 mS/m at FM 700 (locations C304 and C305) and 389 to 474 mS/m at Midway Road (C286 and C287). Farther downstream, conductivities remained elevated at Moss Lake Road (135 to 215 mS/m at C288 to C290) and FM 821 (206 to 280 mS/m at C293). We measured the lowest conductivities along Beals Creek at the most downstream location (123 to 139 mS/m at C276 to C277).

Morgan Creek below Lake Colorado City was the only other tributary where we measured conductivities exceeding 200 mS/m (location C273). Other tributaries having moderate ground conductivities above 100 mS/m include, in downstream order, Bull Creek at FM 2085 near Lake Thomas (109 to 158 mS/m at C251 to C252), Bluff Creek at FM 1606 (98 to 114 mS/m at C253 to C254), Willow Creek at FM 1229 (97 to 103 at C257), Deep Creek at Scurry County Road 4138 (107 to 138 mS/m at C260 to C261), Lone Wolf Creek at Colorado City (45 to 110 mS/m at C265 to C268), and Hackberry Creek (a Beals Creek tributary) at FM 2183 (93 to 150 mS/m at C296 to C297). Beals Creek and these tributaries may contribute saline water to the Colorado River.

We measured relatively low ground conductivities at the remaining tributaries, including (in downstream order) Canyon Creek at FM 1606 (78 to 92 mS/m at C259), Wildhorse Creek at Mitchell County Road 337 (60 to 61 mS/m at C275), Bull Creek (a Beals Creek tributary) at FM 2183 (57 to 87 mS/m at C294 to C295), Red Bank Creek at Mitchell County Road 337 (81 to 100 mS/m at C284), and Walnut Creek at Texas 208 (47 to 70 mS/m at C281). It is unlikely that these tributaries

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. 2 and 3.

Tributary Segment	Locations	VD mS/m	HD mS/m
Bull Creek at FM 2085 (N)	C251 to C252	109-142	122-158
Bluff Creek at FM 1606 (N)	C253 to C254	109-114	98-101
Willow Creek (S)	C257	103	97
Canyon Creek (N)	C259	78	92
Deep Creek (N)	C260 to C261	136-138	107-125
Lone Wolf Creek (N)	C265 to C268	61-110	45-110
Morgan Creek (S)	C273	205	215
Wildhorse Creek (S)	C275	61	60
Beals Creek at FM 700	C304 to C305	214-225	367-397
Beals Creek at Midway Road	C286 to C287	389-428	407-474
Beals Creek at Moss Lake Road	C288 to C290	135-174	138-215
Beals Creek at FM 821	C293	280	206
Bull Creek at FM 2183 (S; Beals Creek tributary)	C294 to C295	74-87	57-62
Hackberry Creek (S; Beals Creek tributary)	C296 to C297	134-150	93-132
Beals Creek at Texas 163	C276 to C277	128-137	123-139
Red Bank Creek (N)	C284	100	81
Walnut Creek (N)	C281	70	47
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

contribute significant saline water to the Colorado River from sources upstream from the measurement points.

CONCLUSIONS

Measurements of surface-water salinities in the Colorado River and its tributaries between Lake Thomas and Lake Spence support previous observations that significant salinity sources degrade Colorado River water quality along this segment and contribute to degraded water quality along Colorado River TMDL segment 1426. Supplemental measurements of shallow ground conductivity along these streams indicate several areas of elevated ground conductivity (and salinity) above Lake Spence, including Colorado River segments below Lake Thomas, upstream from Colorado City, and upstream from Lake Spence and Beals Creek segments extending several kilometers downstream from Big Spring. Surface-water salinities and ground conductivities were generally higher along the Colorado River and its tributaries above Lake Spence than they were along TMDL segment 1426 below Lake Spence.

These October 2004 measurements supplement similar data acquired below Lake Spence in July and August 2004. The combined data set confirms that extending the airborne geophysical survey as described in Paine and Collins (2004) along the Colorado River from Lake Spence to Lake Thomas and along Beals Creek from its confluence with the Colorado River to near Big Spring should help identify additional sources of salinity that degrade Colorado River water quality in TMDL segment 1426.

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APPENDIX A: APPARENT GROUND CONDUCTIVITY MEASUREMENTS

Apparent conductivity measured in the upper Colorado River area, July, August, and October 2004 (figs. 2 and 3). 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)	Date	App. Con. (VD, mS/m)	App. Con (HD, mS/m)	Notes
C003	31.91093	-100.52301	7/20/04	93	80	Lake Spence; Lakeview Recreation Area
C004	31.91091	-100.52313	7/20/04	90	74	Lake Spence; Lakeview Recreation Area
C005	31.91091	-100.52325	7/20/04	89	80	Lake Spence; Lakeview Recreation Area
C006	31.91091	-100.52334	7/20/04	83	93	Lake Spence; Lakeview Recreation Area
C007	31.91089	-100.52341	7/20/04	107	105	Lake Spence; Lakeview Recreation Area
C008	31.91088	-100.52355	7/20/04	121	115	Lake Spence; Lakeview Recreation Area
C009	31.91084	-100.52363	7/20/04	122	123	Lake Spence; Lakeview Recreation Area
C010	31.91083	-100.52374	7/20/04	115	118	Lake Spence; Lakeview Recreation Area
C011	31.91083	-100.52388	7/20/04	127	133	Lake Spence; Lakeview Recreation Area
C012	31.91086	-100.52397	7/20/04	112	140	Lake Spence; Lakeview Recreation Area
C013	31.90407	-100.51304	7/20/04	82	80	Messbox Creek; under power line
C014	31.90417	-100.51302	7/20/04	65	75	Messbox Creek
C015	31.90425	-100.51298	7/20/04	90	77	Messbox Creek
C016	31.90434	-100.51292	7/20/04	98	90	Messbox Creek
C017	31.90444	-100.51289	7/20/04	118	89	Messbox Creek; gravel bar
C018	31.90449	-100.51281	7/20/04	121	100	Messbox Creek
C020	31.87333	-100.51915	7/20/04	85	61	Wildcat Creek
C021	31.87340	-100.51908	7/20/04	68	51	Wildcat Creek
C022	31.87344	-100.51898	7/20/04	59	49	Wildcat Creek
C023	31.87352	-100.51892	7/20/04	65	45	Wildcat Creek
C024	31.87359	-100.51886	7/20/04	70	55	Wildcat Creek
C025	31.87364	-100.51876	7/20/04	64	61	Wildcat Creek
C026	31.87369	-100.51868	7/20/04	67	60	Wildcat Creek
C027	31.87376	-100.51859	7/20/04	61	51	Wildcat Creek
C028	31.91257	-100.58280	7/20/04	71	149	Salt Creek
C029	31.91249	-100.58288	7/20/04	96	159	Salt Creek
C030	31.91241	-100.58292	7/20/04	116	166	Salt Creek
C031	31.91233	-100.58297	7/20/04	102	155	Salt Creek
C032	31.91227	-100.58306	7/20/04	106	152	Salt Creek
C033	31.91219	-100.58311	7/20/04	103	146	Salt Creek
C034	31.91207	-100.58326	7/20/04	101	134	Salt Creek

C035	31.91193	-100.58341	7/20/04	90	122	Salt Creek; boat dock
C036	31.91182	-100.58358	7/20/04	82	181	Salt Creek
C037	31.91172	-100.58376	7/20/04	87	192	Salt Creek
C038	31.91158	-100.58391	7/20/04	96	170	Salt Creek
C039	31.91144	-100.58403	7/20/04	109	152	Salt Creek
C041	31.90674	-100.61230	7/20/04	71	67	Salt Creek; Dripping Springs
C042	31.92918	-100.66157	7/20/04	54	46	Pecan Creek; under power line
C043	31.92912	-100.66166	7/20/04	48	40	Pecan Creek
C044	31.92909	-100.66176	7/20/04	46	43	Pecan Creek
C045	31.92905	-100.66188	7/20/04	48	44	Pecan Creek
C046	31.90317	-100.56874	7/20/04	53	39	Paint Creek
C047	31.90325	-100.56876	7/20/04	47	32	Paint Creek
C048	31.90334	-100.56873	7/20/04	46	36	Paint Creek
C049	31.91828	-100.52989	7/20/04	8	8	Lake Spence; Lakeview Recreation Area; caliche-cemented alluvium
C050	31.91822	-100.53010	7/20/04	9	8	Lake Spence; Lakeview Recreation Area; caliche-cemented alluvium
C051	31.91814	-100.53028	7/20/04	8	7	Lake Spence; Lakeview Recreation Area; caliche-cemented alluvium
C052	31.91804	-100.53046	7/20/04	8	7	Lake Spence; Lakeview Recreation Area; caliche-cemented alluvium
C053	31.98457	-100.54439	7/20/04	47	30	Yellow Wolf Creek
C054	31.98453	-100.54445	7/20/04	58	39	Yellow Wolf Creek
C055	31.89191	-100.49170	7/20/04	87	59	Colorado River; Robert Lee
C056	31.89173	-100.49165	7/20/04	66	50	Colorado River; Robert Lee
C057	31.89155	-100.49170	7/20/04	84	112	Colorado River; Robert Lee
C058	31.89137	-100.49176	7/20/04	83	119	Colorado River; Robert Lee
C059	31.89119	-100.49173	7/20/04	93	104	Colorado River; Robert Lee
C060	31.89101	-100.49181	7/20/04	108	109	Colorado River; Robert Lee
C061	31.89084	-100.49184	7/20/04	102	61	Colorado River; Robert Lee
C062	31.89067	-100.49189	7/20/04	96	74	Colorado River; Robert Lee
C063	31.89048	-100.49185	7/20/04	76	48	Colorado River; Robert Lee
C064	31.89026	-100.49191	7/20/04	64	75	Colorado River; Robert Lee
C065	31.89554	-100.48186	7/21/04	78	55	Mountain Creek; Robert Lee
C066	31.89544	-100.48169	7/21/04	77	54	Mountain Creek; Robert Lee
C067	31.89527	-100.48160	7/21/04	66	49	Mountain Creek; Robert Lee
C068	31.89511	-100.48148	7/21/04	73	55	Mountain Creek; Robert Lee
C069	31.89495	-100.48139	7/21/04	77	51	Mountain Creek; Robert Lee
C070	31.89481	-100.48126	7/21/04	94	87	Mountain Creek; Robert Lee
C071	31.89464	-100.48115	7/21/04	120	120	Mountain Creek; Robert Lee
C072	31.89455	-100.48099	7/21/04	101	67	Mountain Creek; Robert Lee
C073	31.89449	-100.48073	7/21/04	80	67	Mountain Creek; Robert Lee
C074	31.89442	-100.48049	7/21/04	80	50	Mountain Creek; Robert Lee
C075	31.89432	-100.48033	7/21/04	89	67	Mountain Creek; Robert Lee
C077	31.85091	-100.42461	7/21/04	126	95	Colorado River; gravel quarry
C078	31.85089	-100.42441	7/21/04	131	102	Colorado River; gravel quarry
C079	31.85089	-100.42420	7/21/04	145	122	Colorado River; gravel quarry
C080	31.85095	-100.42398	7/21/04	157	142	Colorado River; gravel quarry
C081	31.85097	-100.42377	7/21/04	210	156	Colorado River; gravel quarry

C082	31.85109	-100.42359	7/21/04	267	454	Colorado River; gravel quarry; efflorescence
C083	31.85114	-100.42349	7/21/04	176	528	Colorado River; gravel quarry; efflorescence
C084	31.85115	-100.42339	7/21/04	200	440	Colorado River; gravel quarry; efflorescence
C085	31.85095	-100.42355	7/21/04	252	212	Colorado River; gravel quarry
C086	31.85096	-100.42345	7/21/04	264	210	Colorado River; gravel quarry
C087	31.85093	-100.42336	7/21/04	217	177	Colorado River; gravel quarry
C088	31.85092	-100.42325	7/21/04	247	192	Colorado River; gravel quarry
C089	31.85077	-100.42306	7/21/04	199	155	Colorado River; gravel quarry
C091	31.85333	-100.42340	7/21/04	131	80	Machae Creek
C092	31.85323	-100.42322	7/21/04	155	127	Machae Creek
C093	31.85303	-100.42318	7/21/04	205	151	Machae Creek
C094	31.85290	-100.42302	7/21/04	189	144	Machae Creek
C095	31.85273	-100.42296	7/21/04	205	153	Machae Creek
C096	31.85265	-100.42304	7/21/04	198	223	Machae Creek
C097	31.85251	-100.42299	7/21/04	171	224	Machae Creek
C098	31.85249	-100.42288	7/21/04	190	170	Machae Creek
C099	31.85353	-100.42349	7/21/04	113	88	Machae Creek
C100	31.85366	-100.42364	7/21/04	97	77	Machae Creek
C101	31.85374	-100.42378	7/21/04	73	62	Machae Creek
C102	31.87520	-100.36633	7/21/04	85	62	Turkey Creek
C103	31.87495	-100.36625	7/21/04	72	47	Turkey Creek
C104	31.87521	-100.35274	7/21/04	55	31	Double Barrel Creek
C105	31.87506	-100.35288	7/21/04	60	40	Double Barrel Creek
C106	31.86697	-100.29258	7/21/04	73	54	Kickapoo Creek at U.S. 277
C107	31.86701	-100.29279	7/21/04	78	54	Kickapoo Creek at U.S. 277
C108	31.86707	-100.29287	7/21/04	79	63	Kickapoo Creek at U.S. 277
C109	31.86714	-100.29297	7/21/04	83	58	Kickapoo Creek at U.S. 277
C110	31.84702	-100.28923	7/21/04	90	78	Colorado River; U.S. 277 to Kickapoo Creek
C111	31.84709	-100.28920	7/21/04	88	100	Colorado River; U.S. 277 to Kickapoo Creek
C112	31.84697	-100.28788	7/21/04	115	211	Kickapoo Creek; mouth
C113	31.84700	-100.28811	7/21/04	137	120	Kickapoo Creek; mouth
C114	31.84667	-100.28677	7/21/04	99	46	Kickapoo Creek; mouth
C115	31.84716	-100.28682	7/21/04	108	130	Kickapoo Creek
C116	31.84710	-100.28683	7/21/04	136	97	Kickapoo Creek
C117	31.84679	-100.28734	7/21/04	69	120	Colorado River; near Kickapoo Creek confluence
C118	31.84684	-100.28718	7/21/04	128	115	Colorado River; near Kickapoo Creek confluence
C119	31.84679	-100.28714	7/21/04	121	131	Colorado River; near Kickapoo Creek confluence
C120	31.84670	-100.28703	7/21/04	118	116	Colorado River; near Kickapoo Creek confluence
C121	31.84668	-100.28692	7/21/04	101	129	Colorado River; near Kickapoo Creek confluence
C123	31.84791	-100.29660	7/21/04	109	80	Colorado River; upstream from U.S. 277
C124	31.84792	-100.29650	7/21/04	91	76	Colorado River; upstream from U.S. 277

C125	31.84792	-100.29639	7/21/04	88	78	Colorado River; upstream from U.S. 277
C126	31.84789	-100.29628	7/21/04	96	85	Colorado River; upstream from U.S. 277
C127	31.84789	-100.29617	7/21/04	90	90	Colorado River; upstream from U.S. 277
C128	31.84789	-100.29606	7/21/04	85	85	Colorado River; upstream from U.S. 277
C129	31.84437	-100.22253	7/22/04	60	42	Hog Creek
C130	31.84418	-100.22266	7/22/04	53	41	Hog Creek
C131	31.84406	-100.22276	7/22/04	57	48	Hog Creek
C132	31.84392	-100.22290	7/22/04	56	40	Hog Creek
C133	31.80920	-100.21784	7/22/04	102	98	Colorado River; county road crossing
C134	31.80934	-100.21771	7/22/04	88	79	Colorado River; county road crossing
C135	31.80937	-100.21767	7/22/04	92	82	Colorado River; county road crossing
C136	31.80937	-100.21755	7/22/04	88	82	Colorado River; county road crossing
C137	31.80941	-100.21738	7/22/04	96	94	Colorado River; county road crossing
C138	31.84610	-100.19607	7/22/04	107	89	Oak Creek
C139	31.84600	-100.19590	7/22/04	106	92	Oak Creek
C140	31.84588	-100.19573	7/22/04	101	89	Oak Creek
C141	31.84577	-100.19557	7/22/04	106	95	Oak Creek
C142	31.84561	-100.19545	7/22/04	113	115	Oak Creek
C143	31.84543	-100.19542	7/22/04	114	129	Oak Creek
C144	31.84526	-100.19548	7/22/04	114	118	Oak Creek; at seep
C145	31.84507	-100.19554	7/22/04	126	124	Oak Creek
C146	31.84491	-100.19573	7/22/04	100	124	Oak Creek
C147	31.84479	-100.19589	7/22/04	106	95	Oak Creek
C148	31.84472	-100.19615	7/22/04	102	103	Oak Creek
C149	31.84464	-100.19638	7/22/04	114	122	Oak Creek
C150	31.79261	-100.18478	7/22/04	80	93	Colorado River; upstream from FM 3115 bridge; in river
C151	31.79271	-100.18545	7/22/04	83	71	Colorado River; upstream from FM 3115 bridge
C152	31.79266	-100.18532	7/22/04	73	65	Colorado River; upstream from FM 3115 bridge
C153	31.79268	-100.18523	7/22/04	79	77	Colorado River; upstream from FM 3115 bridge
C154	31.79267	-100.18513	7/22/04	81	71	Colorado River; upstream from FM 3115 bridge
C155	31.79267	-100.18502	7/22/04	81	68	Colorado River; upstream from FM 3115 bridge
C156	31.79263	-100.18493	7/22/04	86	81	Colorado River; upstream from FM 3115 bridge
C157	31.79236	-100.18434	7/22/04	62	79	Colorado River; downstream from FM 3115 bridge
C158	31.79234	-100.18426	7/22/04	65	78	Colorado River; downstream from FM 3115 bridge
C159	31.79231	-100.18417	7/22/04	72	88	Colorado River; downstream from FM 3115 bridge

C160	31.81908	-100.05254	7/22/04	99	75	Valley Creek
C161	31.81926	-100.05264	7/22/04	110	78	Valley Creek
C162	31.81942	-100.05273	7/22/04	113	116	Valley Creek
C163	31.81959	-100.05277	7/22/04	114	112	Valley Creek
C164	31.81977	-100.05283	7/22/04	125	105	Valley Creek
C165	31.77918	-100.03287	7/22/04	88	63	Valley Creek
C166	31.77900	-100.03284	7/22/04	87	72	Valley Creek
C167	31.77883	-100.03289	7/22/04	89	66	Valley Creek
C168	31.77864	-100.03293	7/22/04	88	57	Valley Creek
C169	31.75831	-100.05142	7/22/04	106	88	Quarry Creek
C170	31.75847	-100.05156	7/22/04	109	85	Quarry Creek
C171	31.75853	-100.05175	7/22/04	92	65	Quarry Creek
C173	31.71485	-100.02673	7/22/04	86	74	Colorado River; downstream from FM 2111 bridge
C174	31.71486	-100.02673	7/22/04	78	76	Colorado River; downstream from FM 2111 bridge
C175	31.71484	-100.02666	7/22/04	88	101	Colorado River; downstream from FM 2111 bridge; in river
C176	31.71494	-100.02651	7/22/04	86	114	Colorado River; downstream from FM 2111 bridge
C177	31.73634	-99.98963	7/22/04	97	147	Los Arroyos
C178	31.73635	-99.98944	7/22/04	105	112	Los Arroyos
C179	31.73635	-99.98921	7/22/04	98	101	Los Arroyos
C180	31.73653	-99.98903	7/22/04	104	115	Los Arroyos
C181	31.78535	-99.94610	7/22/04	55	50	Elm Creek
C182	31.78547	-99.94595	7/22/04	64	41	Elm Creek
C183	31.78559	-99.94579	7/22/04	62	45	Elm Creek
C184	31.73000	-99.94186	7/22/04	90	62	Colorado River; U.S. 83 bridge; on terrace 1m above river
C185	31.73004	-99.94210	7/22/04	90	68	Colorado River; U.S. 83 bridge; on terrace 1m above river
C186	31.73258	-99.95472	7/22/04	163	105	Colorado River; U.S. 67 bridge; under bridge
C199	31.73876	-99.88884	8/3/04	85	78	Bears Foot Creek; County Road 122
C200	31.73860	-99.88874	8/3/04	93	97	Bears Foot Creek; County Road 122
C201	31.70955	-99.83671	8/3/04	83	60	Mustang Creek at county road
C202	31.70941	-99.83673	8/3/04	70	49	Mustang Creek at county road
C203	31.70905	-99.83675	8/3/04	86	69	Mustang Creek at county road
C204	31.70879	-99.83680	8/3/04	75	60	Mustang Creek at county road
C205	31.70856	-99.83681	8/3/04	75	53	Mustang Creek at county road
C207	31.63603	-99.83225	8/3/04	56	46	Colorado River; County Road 129
C209	31.69229	-99.91707	8/3/04	89	81	Spur Creek; County Road 114
C210	31.69237	-99.91681	8/3/04	102	111	Spur Creek; County Road 114
C211	31.71016	-100.02246	8/3/04	72	56	Rocky Creek; County Road 287
C212	31.71011	-100.02256	8/3/04	78	54	Rocky Creek; County Road 287
C213	31.70768	-100.06100	8/3/04	101	84	Indian Creek; County Road 287
C214	31.71207	-100.10652	8/3/04	111	129	Red Bank Creek
C215	31.71233	-100.10643	8/3/04	98	103	Red Bank Creek
C216	31.72561	-100.14081	8/3/04	71	56	Antelope Creek
C217	31.72539	-100.14096	8/3/04	55	58	Antelope Creek
C218	31.76844	-100.21734	8/3/04	85	65	Mule Creek

C219	31.76839	-100.21769	8/3/04	75	60	Mule Creek
C220	31.79256	-100.25263	8/3/04	63	65	Juniper Creek
C221	31.79248	-100.25251	8/3/04	87	76	Juniper Creek
C222	31.79243	-100.25244	8/3/04	88	95	Juniper Creek
C223	31.82520	-100.31650	8/3/04	34	26	Live Oak Creek tributary
C224	31.82504	-100.31648	8/3/04	34	30	Live Oak Creek tributary
C225	31.82854	-100.32744	8/3/04	25	24	Live Oak Creek
C226	31.82865	-100.32747	8/3/04	30	22	Live Oak Creek
C227	31.82889	-100.32743	8/3/04	28	20	Live Oak Creek
C229	31.84775	-100.43790	8/3/04	94	66	Jack Miles Creek
C230	31.84783	-100.43791	8/3/04	99	74	Jack Miles Creek
C231	31.83588	-100.43149	8/3/04	80	38	Buffalo Creek
C232	31.83607	-100.43146	8/3/04	50	34	Buffalo Creek
C233	31.83615	-100.43152	8/3/04	42	37	Buffalo Creek
C234	31.83631	-100.43151	8/3/04	48	46	Buffalo Creek
C235	31.83649	-100.43153	8/3/04	74	51	Buffalo Creek
C237	32.01964	-100.73653	8/3/04	170	200	Colorado River; RR 2059 bridge
C238	32.01964	-100.73627	8/3/04	180	298	Colorado River; RR 2059 bridge
C239	31.97891	-100.58553	8/3/04	71	64	Rough Creek
C240	31.97896	-100.58539	8/3/04	84	79	Rough Creek
C241	31.97906	-100.58527	8/3/04	95	84	Rough Creek
C242	31.97919	-100.58524	8/3/04	135	107	Rough Creek
C243	31.97929	-100.58512	8/3/04	127	98	Rough Creek
C245	32.62784	-101.28577	10/26/04	56	47	Colorado River; FM 1205 bridge
C246	32.62872	-101.28560	10/26/04	146	154	Colorado River; FM 1205 bridge
C250	32.58429	-101.13025	10/26/04	121	153	Colorado River; FM 1298 bridge
C251	32.59886	-101.09421	10/26/04	142	122	Bull Creek; FM 2085 bridge
C252	32.59947	-101.09413	10/26/04	109	158	Bull Creek; FM 2085 bridge
C253	32.59221	-101.05031	10/26/04	114	101	Bluff Creek; FM 1606 bridge
C254	32.59240	-101.05027	10/26/04	109	98	Bluff Creek; FM 1606 bridge
C255	32.53889	-101.05501	10/26/04	425	275	Colorado River; Texas 350 bridge
C257	32.51109	-101.05679	10/26/04	103	97	Willow Creek; FM 1229 bridge
C258	32.54445	-100.96855	10/26/04	246	203	Colorado River; FM 2835 bridge
C259	32.57486	-100.96207	10/26/04	78	92	Canyon Creek; FM 1606 bridge
C260	32.54425	-100.88492	10/26/04	138	125	Deep Creek; Scurry County Road 4138
C261	32.54414	-100.88489	10/26/04	136	107	Deep Creek; Scurry County Road 4138
C262	32.47826	-100.94913	10/26/04	220	260	Colorado River; FM 1808 bridge
C263	32.44178	-100.94920	10/26/04	207	155	Colorado River at Mitchell County Road 167; Cedar Bend bridge
C265	32.39344	-100.85077	10/27/04	83	102	Lone Wolf Creek at Ruddick Park, Colorado City
C266	32.39331	-100.85095	10/27/04	110	110	Lone Wolf Creek at Ruddick Park, Colorado City
C267	32.39261	-100.85111	10/27/04	84	45	Lone Wolf Creek at Ruddick Park, Colorado City
C268	32.39262	-100.85120	10/27/04	61	56	Lone Wolf Creek at Ruddick Park, Colorado City
C269	32.38928	-100.87327	10/27/04	286	158	Colorado River; State Spur 377 bridge
C270	32.38940	-100.87319	10/27/04	166	186	Colorado River; State Spur 377 bridge

C271	32.38952	-100.87319	10/27/04	154	180	Colorado River; State Spur 377 bridge
C272	32.38515	-100.86510	10/27/04	124	137	Colorado River; Texas 163 bridge
C273	32.31600	-100.91794	10/27/04	205	215	Morgan Creek; Texas 163 bridge
C275	32.24941	-100.97229	10/27/04	61	60	Wildhorse Creek; Mitchell County Road 337
C276	32.19927	-101.01380	10/27/04	128	139	Beals Creek; downstream fromTexas 163 bridge
C277	32.19921	-101.01378	10/27/04	137	123	Beals Creek; downstream fromTexas 163 bridge
C278	32.20992	-100.87275	10/27/04	123	139	Colorado River; Mitchell County Road 337
C281	32.12869	-100.73418	10/27/04	70	47	Walnut Creek; Texas 208
C284	32.20338	-100.78577	10/27/04	100	81	Red Bank Creek; Mitchell County Road 337
C286	32.25701	-101.41743	10/28/04	389	407	Beals Creek; Midway Road
C287	32.25714	-101.41743	10/28/04	428	474	Beals Creek; Midway Road
C288	32.24896	-101.36224	10/28/04	174	138	Beals Creek; Moss Lake Road
C289	32.24897	-101.36217	10/28/04	166	153	Beals Creek; Moss Lake Road
C290	32.24899	-101.36213	10/28/04	135	215	Beals Creek; Moss Lake Road
C293	32.21249	-101.21040	10/28/04	280	206	Beals Creek; FM 821 bridge
C294	32.14169	-101.18821	10/28/04	74	62	Bull Creek; FM 2183
C295	32.14190	-101.18822	10/28/04	87	57	Bull Creek; FM 2183
C296	32.17102	-101.02146	10/28/04	150	132	Hackberry Creek; FM 2183
C297	32.17099	-101.02149	10/28/04	134	93	Hackberry Creek; FM 2183
C298	32.39965	-100.89426	10/28/04	265	376	Colorado River; I-20 bridge
C299	32.39981	-100.89428	10/28/04	258	290	Colorado River; I-20 bridge
C300	32.39987	-100.89425	10/28/04	204	238	Colorado River; I-20 bridge
C301	32.39996	-100.89427	10/28/04	250	316	Colorado River; I-20 bridge
C304	32.25777	-101.43190	10/28/04	214	367	Beals Creek; FM 700 bridge
C305	32.25784	-101.43209	10/28/04	225	397	Beals Creek; FM 700 bridge

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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 (figs. 2 and 3) in August and October 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)	Date	Temp. (deg. C)	App. Con. (mS/m)	TDS (mg/L)	Notes
C187	31.91060	-100.52474	8/2/04	32.2	295	1470	Lake Spence; Lakeview Recreation Area (ponded)
C188	31.91212	-100.58331	8/2/04	37.3	702	3510	Salt Creek (ponded)
C189	31.89188	-100.49169	8/2/04	35.4	298	1490	Colorado River; Robert Lee
C190	31.85075	-100.42468	8/2/04	31.9	305	1520	Colorado River; gravel quarry; upstream from efflorescence
C191	31.85092	-100.42321	8/2/04	32.0	307	1520	Colorado River; gravel quarry; downstream from efflorescence
C192	31.84788	-100.29204	8/2/04	34.6	259	1290	Colorado River; U.S. 277 bridge
C193	31.80924	-100.21784	8/2/04	35.1	295	1470	Colorado River; county road crossing
C194	31.79256	-100.18473	8/2/04	34.2	225	1120	Colorado River; FM 3115 bridge
C195	31.71484	-100.02668	8/2/04	34.7	285	1430	Colorado River; downstream from FM 2111 bridge
C196	31.78535	-99.94621	8/2/04	34.5	151	810	Elm Creek at county road
C197	31.74993	-99.94532	8/2/04	31.3	146	732	Elm Creek at Ballinger City Park
C198	31.73241	-99.95474	8/3/04	29.5	259	1370	Colorado River; U.S. 67 bridge
C203	31.70905	-99.83675	8/3/04	28.2	84	426	Mustang Creek at county road (ponded)
C206	31.63588	-99.83225	8/3/04	31.9	156	777	Colorado River; County Road 129
C213	31.70768	-100.06100	8/3/04	30.7	44	218	Indian Creek; County Road 287 (ponded)
C228	31.82847	-100.32753	8/3/04	37.2	20	100	Live Oak Creek (ponded)
C236	32.01974	-100.73617	8/3/04	33.2	118	590	Colorado River; RR 2059 bridge
C244	32.21888	-101.47628	10/25/04	19.4	48	247	Big Spring historic site, Cosden Lake area (ponded)
C246	32.62872	-101.28560	10/26/04	18.5	299	1500	Colorado River; FM 1205 bridge
C248	32.57993	-101.13673	10/26/04	20.0	63	314	Lake J. B. Thomas; south end of dam (ponded)
C249	32.57742	-101.14325	10/26/04	20.2	62	313	Lake J. B. Thomas; south end of dam (ponded)
C250	32.58429	-101.13025	10/26/04	19.5	29	149	Colorado River; FM 1298 bridge (ponded)
C251	32.59886	-101.09421	10/26/04	21.3	327	1670	Bull Creek; FM 2085 bridge
C256	32.53888	-101.05494	10/26/04	24.0	681	3400	Colorado River; Texas 350 bridge

C257	32.51109	-101.05679	10/26/04	22.8	57	284	Willow Creek; FM 1229 bridge (ponded)
C258	32.54445	-100.96855	10/26/04	24.2	736	3690	Colorado River; FM 2835 bridge
C260	32.54425	-100.88492	10/26/04	20.0	83	415	Deep Creek; Scurry County Road 4138
C262	32.47826	-100.94913	10/26/04	23.5	489	2450	Colorado River; FM 1808 bridge
C263	32.44178	-100.94920	10/26/04	23.3	421	2111	Colorado River at Mitchell County Road 167; Cedar Bend bridge
C264	32.39378	-100.85053	10/27/04	20.2	162	807	Lone Wolf Creek at Ruddick Park, Colorado City
C269	32.38928	-100.87327	10/27/04	20.7	687	3460	Colorado River; State Spur 377 bridge
C272	32.38515	-100.86510	10/27/04	19.7	635	3170	Colorado River; Texas 163 bridge
C273	32.31600	-100.91794	10/27/04	20.6	572	2870	Morgan Creek; Texas 163 bridge (ponded)
C274	32.33939	-100.92881	10/27/04	20.6	427	2150	Lake Colorado City State Park (ponded)
C276	32.19927	-101.01380	10/27/04	21.6	338	1690	Beals Creek; downstream fromTexas 163 bridge
C278	32.20992	-100.87275	10/27/04	21.3	450	2250	Colorado River; Mitchell County Road 337
C279	31.91054	-100.52452	10/27/04	21.2	267	1330	Lake Spence; Lakeview Recreation Area (ponded)
C280	32.01966	-100.73613	10/27/04	21.5	307	1540	Colorado River; RR 2059 bridge
C285	32.25676	-101.41756	10/28/04	20.9	1630	8160	Beals Creek; Midway Road
C288	32.24896	-101.36224	10/28/04	19.4	910	4550	Beals Creek; Moss Lake Road
C291	32.24375	-101.31224	10/28/04	20.6	299	1490	Moss Creek Reservoir (ponded)
C293	32.21249	-101.21040	10/28/04	20.6	1003	5040	Beals Creek; FM 821 bridge
C302	32.39986	-100.89420	10/28/04	26.5	1205	6030	Colorado River; I-20 bridge
C303	32.44176	-100.94902	10/28/04	21.9	479	2390	Colorado River at Mitchell County Road 167; Cedar Bend Bridge
C305	32.25784	-101.43209	10/28/04	23.2	–	> 10,000	Beals Creek; FM 700 bridge