Phase II
Investigation Report

Wendkirk Oil Field
Phase II Investigation
Coke County, Texas

Prepared for:

Railroad Commission of Texas
Oil and Gas Division
Site Remediation and Special Response

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August 2007

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1.0 INTRODUCTION

This report documents the Phase II investigation activities completed within the Machae Creek Area along the Upper Colorado River southeast of Robert Lee, Coke County, Texas. The Phase II investigation focused on the Wendkirk Oil Field, which is located at the downstream extent of the Machae Creek Area.

1.1 Site Background

Segment 1426 of the Upper Colorado River was placed on the Texas Commission on Environmental Quality (TCEQ) Total Maximum Daily Load (TMDL) 303(d) list due to high salinity that prevents the river segment from meeting surface water quality standards. Segment 1426 is located between E. V. Spence Reservoir and O. H. Ivie Reservoir in Coke and Runnels Counties. Previous analyses of the salinity in the Colorado River have indicated that salinity concentrations increase downstream of the Wendkirk Oil Field.

The Railroad Commission of Texas (RRC), Oil and Gas Division, has received a Section 319 Non-Point Source grant from the United States Environmental Protection Agency (EPA) through the TCEQ to determine if oil and gas operations in the Wendkirk Oil Field are contributing to the high saline water. The overall objective of the project is to define the nature and extent of potential sources leading to the high salinity in the Colorado River and to evaluate best management practices (BPMs) to abate the source(s).

As part of a TCEQ TMDL project, an airborne geophysical survey of Segment 1426 was conducted by the University of Texas Bureau of Economic Geology (BEG) for the TCEQ (BEG, 2005). This survey indicated four areas of elevated ground conductivity along the Upper Colorado River. The most upstream area, referred to as the Machae Creek Area, is the subject of the investigation presented in this report. Within the Machae Creek Area, the Colorado River is 17 kilometers long and has several intermittent tributaries. The Wendkirk Oil Field is located at the downstream extent of the Machae Creek Area as illustrated in Figure 1.

In December 2005, TRC conducted a preliminary investigation with the objective of reviewing available records and data and conducting a site reconnaissance to support development of further investigation activities. The results of the preliminary investigation were documented in a memorandum submitted to RRC on April 20, 2006 (TRC, 2006a). The approach for Phase II investigation activities included conducting three seasonal water sampling events and the completion of a two-phase groundwater investigation.

1.2 Investigation Objectives

Based upon the results of the preliminary investigation conducted by TRC, it was determined that further investigation activities were warranted. The objective of the Phase II investigation was to gather additional information that could be used to determine the nature and extent of O&G E&P source(s), if found, leading to the high salinity in the Machae Creek Area of the Colorado River. This information would in turn be used to design BMPs to reduce salinity contributions to the Colorado River from impacted groundwater.

1.3 Report Contents

This Phase II Investigation Report summarizes the site investigation field methods, details the field activities performed at the site, presents the results of the site investigation, and provides conclusions and recommendations for the next step in developing BMPs to address impacted groundwater at the site.

2.0 INVESTIGATION METHODS

TRC conducted Phase II site investigation activities in and near the Wendkirk Oil Field beginning in July 2006 through April 2007. Mr. Brian Floyd, Site Remediation Coordinator for the RRC District 7C, was present during these field activities. The investigation was conducted in accordance with the following documents:

- *Final Seasonal Water Monitoring Work Plan, Wendkirk Oil Field Phase II Investigation* (TRC, 2006b) submitted to the RRC by TRC in July 2006.
- *Final Groundwater Investigation Work Plan, Wendkirk Oil Field Phase II Investigation* (TRC, 2006c) submitted to the RRC by TRC in August 2006.
- *Final – Revision 1 Seasonal Water Monitoring Work Plan, Wendkirk Oil Field Phase II Investigation* (TRC, 2006d) submitted to the RRC by TRC in December 2006.
- *Final – Revision 1 Groundwater Investigation Work Plan, Wendkirk Oil Field Phase II Investigation* (TRC, 2006e) submitted to the RRC by TRC in December 2006.
- *Investigations and Abatement of Produced Water Impacts and Seeps to Surface Water in the Upper Colorado River Basin Downstream of Spence Reservoir (Segment 1426) Quality Assurance Project Plan* (RRC, 2005) submitted by the RRC to the TCEQ and USEPA in September 2005.
- *Investigations and Abatement of Produced Water Impacts and Seeps to Surface Water in the Upper Colorado River Basin Downstream of Spence Reservoir (Segment 1426) Quality Assurance Project Plan – Revision 1* (RRC, 2007) submitted by the RRC to the TCEQ and USEPA in February 2007. Approved February 1, 2007.

The field investigation consisted of the following tasks: (1) seasonal water monitoring, including stream flow measurements and river gauging; (2) surface water sampling and water well sampling; (3) groundwater investigation/monitoring well installation, synoptic well and river gauging, and groundwater sample collection from monitoring wells; (4) geophysical investigation; (5) surveying wells and river gauging stations; and (6) managing investigation-derived waste (IDW).

The field investigation tasks were completed in accordance with the Work Plan and QAPP with the following variances:

- Water well 4313606 (Mays property, south of Colorado River) was dry; therefore, a sample was not collected from the well. An attempt to sample water wells 4314103

(Rawlings property, south of Colorado River) and 4314404 (Rawlings property, south of Colorado River) was made but 4314103 was dry and 4314404 could not be located. Water wells 4313605 (Mays property, south of Colorado River), 4313608 (Mays property, south of Colorado River), and Rawlings were sampled instead.

- Only one surface water sample (upstream) could be collected from May's Ranch Creek during July 2006 and August 2006 due to the creek being dry on the downstream end.
- Due to a drop in discharge, only one water sample could be collected from spring 4314102 (Mays property, south of Colorado River) because discharge dropped during July and August 2006.
- A surface water sample could not be collected from Colorado River segment 8 (BEG designation, Figure 2) during the second and third seasonal water monitoring events due to property access issues.
- Surface water samples could not be collected from Colorado River segment 16 (BEG designation, Figure 2) during any of the seasonal water monitoring events due to limited access to the target area (i.e., steep topography and heavy vegetation).
- Three additional water wells (Mays-01, Milford-01, and Milford-02) located within the Wendkirk Oil Field were found while conducting file reviews or investigation activities. The wells were added to the seasonal water sampling list. These three wells were also surveyed and gauged. The groundwater elevations were used in conjunction with the data collected from the monitoring wells to determine the groundwater flow direction and gradient.

2.1 Seasonal Water Monitoring

Seasonal water monitoring consisted of collecting stream flow measurements at two locations along the Colorado River, sampling surface water along the Colorado River, sampling surface water from other locations (i.e., creeks, quarry pond, seeps, and springs), sampling water wells in the Wendkirk Oil Field area, and investigating the area north of Colorado River Segments 7 and 8 as a potential source area for the elevated chloride concentrations. Seasonal water sampling was conducted in accordance with the *Seasonal Water Sampling Work Plan* dated July 2006 and December 2006. A summary of the seasonal sample locations, sample identifications, sample dates, and laboratory analyses are presented in Table 1. The following sections describe the seasonal water monitoring activities completed during the Phase II Investigation activities.

2.1.1 Stream Flow Measurements and River Gauging Measurements

During each seasonal monitoring event, stream flow was measured at two specific points, SF-01 located upstream and SF-02 located downstream of the Machae Creek Area (Figure 2). Stream flow measurements and calculated discharge rates were recorded on Stream Flow Measurement Forms. Copies of these field forms are located in Appendix A.

River gauging stations were installed along Colorado River segments 13, 14, and 15 during April 19, 2007. The stations were constructed with a metal T-post installed in the river bed. Stations RG-01 and RG-02 were installed along portions of the river protected from flooding events (e.g. behind trees). Station RG-03 was installed in an unprotected location due to installation limitations from bedrock outcrops along the base of the Colorado River along segment 15. The top of the T-posts were surveyed during April 2007 so river elevations could be determined by measuring from the top of the T-post to the water level in the river at each location. The river elevations were calculated by subtracting the distance to water from the surveyed top of the T-post at each station.

2.1.2 Surface Water Sampling

Surface water samples were collected along the Colorado River beginning with one from segment 3 and then one sample every kilometer (i.e., per BEG segment) from segments 7 through 15. Two surface water samples were collected at different locations along segment 17 because segment 16 was not accessible. Additionally, surface water samples were collected from creeks, springs, seeps, and ponds near the Wendkirk Oil Field. During certain seasonal sampling events, samples could not be collected from all of the surface water features due to the lack of water in some of the creeks and springs. Upstream and downstream surface water samples were collected from the creek flowing through May's Ranch and from a surface water pond located at the SANCO quarry. Samples were collected directly from the east and west locations of Spring 4314102 (Mays property, south of Colorado River) and from the Mar's Ranch Seep. Due to low flow conditions and the configuration of the spring, Spring 4314104 (Milford property, north of Colorado River) was sampled by collecting water from a surface pool near the outfall of the spring. During July 2006, a surface water sample (W-O-01) also was collected from a pond located north of segments 7 and 8 and was analyzed for chlorides using a field test kit. Surface water sample locations are depicted in Figure 2. The surface water samples were collected in accordance with the approved Work Plan and the QAPP.

2.1.3 Water Well Sampling

Sample collection from several water wells located near the Wendkirk Oil Field was proposed in the *Seasonal Water Monitoring Work Plan*. Water wells 4313606 (Mays property, south of Colorado River) and 4314103 (Rawlings property, south of Colorado River) however, were dry, so a sample could not be collected from those wells. Water well 4314404 (Rawlings property, south of Colorado River) was also not sampled because it could not be located. Water wells 4313605 (Mays property, south of Colorado River), 4313608 (Mays property, south of Colorado River), and Rawlings were sampled as replacement wells. Three additional water wells (Mays-01, Milford-01, and Milford-02) located within or near the Wendkirk Oil Field were found while conducting file reviews or investigation activities. These three wells were also surveyed and gauged for depth to groundwater and added to the seasonal water sampling list. Water wells 4313302 (Ivey property, north of Colorado River) and 4313603 (Mays property, south of Colorado River) were sampled as proposed. The groundwater elevations collected from the water wells were used in conjunction with the data collected from the monitoring wells to determine the groundwater flow direction and gradient.

2.2 Groundwater Investigation

A groundwater investigation was completed in the Wendkirk Oil Field to evaluate potential impacts to groundwater from historical oil field activities. Groundwater investigation activities were conducted in accordance with the *Groundwater Investigation Work Plan* dated July 2006 and December 2006 and followed the QAPP. A summary of the groundwater sample locations, sample identifications, sample dates, and laboratory analyses are presented in Table 1. The following sections describe the groundwater investigation activities completed to date.

2.2.1 Monitoring Well Installation

Nine groundwater monitoring wells (MW-01 through MW-09) were installed during the first groundwater investigation in August 2006. The well locations were not altered from the locations proposed in the *Groundwater Investigation Work Plan* dated July 2006. An additional nine monitoring wells (MW-10 through MW-18) were installed in April 2007 during the second groundwater investigation. The locations of these wells were determined based on the results of the first groundwater investigation and the BEG geophysical investigation. The wells were installed using a combination hollow stem auger (HSA)/air rotary drilling rig. Upon completion, the wells were developed using disposable PVC bailers or a submersible pump. The soil boring/well completion logs are presented in Appendix B. The monitoring well locations are depicted on Figure 2.

2.2.2 Well Gauging

Groundwater level measurements were collected from monitoring wells and water wells using a water level meter on August 30, 2006, October 26, 2006, and April 20, 2007. Table 2 presents the monitoring well information including ground elevation, top of well casing elevation, water level measurement (date of measurement, depth to water, and total depth), and calculated water elevation. These data were used to assist in determining the groundwater flow direction and gradient.

2.2.3 Groundwater Sampling

Groundwater sampling was conducted at the eighteen monitoring wells installed during the investigation activities in accordance with the groundwater investigation work plans and the QAPP. Samples were collected using disposable PVC bailers. The groundwater quality parameters were documented on the field sampling forms which are presented in Appendix A. The DHL laboratory analytical reports from these groundwater sampling events are included in Appendix C.

2.3 Produced Water Sampling

A water sample was collected from the salt water disposal facility (SWDF) Salmon #1 SWD 06788 located in the Wendkirk Oil Field. The location of the SWDF is depicted in Figure 2. The facility consists of a tank battery with three above ground storage tanks, pumping equipment, and an injection well. The SWDF collects produced water from a few remaining oil wells that operate in the Wendkirk Oil Field. The water is disposed via the injection well located immediately northwest of the disposal facility tank battery. The water sample was collected from the tank by opening the discharge valve and filling the sample bottles directly from the valve.

2.4 Geophysical Investigation

In October and November 2006, the BEG conducted surface and borehole geophysical surveys in the Wendkirk Oil Field. The objective of the geophysical investigation was to help determine the lateral and vertical extent of salinization in and around the Wendkirk Oil Field area prior to completing the second groundwater investigation event. The BEG used the electromagnetic induction (EM) method, which measures the electrical conductivity of the ground, to delineate salinization because ground conductivity is greatly influenced by pore-water salinity. Three types of EM data were acquired to further characterize salinization, including borehole logs, ground conductivity measurements along transects at the ground surface, and vertical time-domain EM “soundings” to examine changes in ground conductivity from the ground surface to depths of 50 to 100 meters. The following EM investigation activities were completed by the BEG:

- Borehole EM logging was completed at the Mays-01 well and at the groundwater monitor wells MW-01 through MW-09 using a Geonics Gamma 39 borehole probe.

- Apparent conductivity was measured at the ground surface along 12 transects using a Geonics EM34-3 frequency-domain EM instrument. EM surveys were completed across transect lines where August 2006 analytical data indicated elevated groundwater salinization and at former oil field operation locations (e.g. pits and well locations) determined from historical aerial photographs.

- Time-domain EM (TDEM) soundings were conducted at five locations to examine changes in ground conductivity to greater depths than those reached by existing water and monitoring wells. Two TDEM soundings (TDEM 1 and TDEM 2) were located north of the Colorado River and three (TDEM 3, TDEM 4, and TDEM 5) were located south of the river.

- The EM methods used during the investigation are described in the BEG report *Surface and Borehole Geophysical Investigations in the Wendkirk Oil Field Area, Coke County, Texas* dated May 2007. The location of the transect lines and TDEM sounding locations are presented in the BEG report located in Appendix D (Figure 2).

2.5 Surveying

Upon completion of the monitoring well drilling, a survey was conducted during August 2006 and April 2007 by SKG Surveying of San Angelo, Texas. A coordinate survey of the eighteen monitoring wells, existing water wells (Mays-01, Milford-01, and Milford-02), and TRC river gauging stations was completed using a GPS unit. In addition, the GPS unit was used to survey the ground and top-of-casing elevation at the monitoring wells, water wells; and the elevation of the river gauging stations installed by TRC to an accuracy of 0.01 feet. The survey was referenced using two United States Geological Survey (USGS) monuments identified in the SKG survey report as USGS Mon. Q1175 and USGS Mon. ROLL-E.T. for latitude/longitude coordinates and elevation. Copies of the SKG survey reports are included in Appendix E.

2.6 Investigation Derived Waste Management

Soil cuttings from the well installation were initially placed on and covered with a plastic sheet. Because a majority of the monitoring well locations exhibited no signs of hydrocarbon impacts, the soil cuttings were removed from the plastic sheet and spread along the ground surface. A slight unknown odor was observed during installation of MW-02. The soil cuttings from this location were removed from the plastic sheet and placed in one 55-gallon drum for disposal. The water from groundwater sampling, well development, and decontamination was staged in 55-gallon steel drums. A total of six (1 soil and 5 water) drums were staged near MW-04, and one water drum was staged next to MW-13. The drums containing the soil cuttings and water will be disposed during 2007.

3.0 SITE GEOLOGY/HYDROGEOLOGY

This section presents the geologic and hydrogeologic information near the Machae Creek Area along the Upper Colorado River southeast of Robert Lee, Coke County, Texas.

3.1 Geology

The Wendkirk Oil Field (study area) is located in Coke County approximately 5 miles southeast of Robert Lee along the Colorado River. The study area lies in the Central Texas section of the Great Plains physiographic province, which is characterized by rolling hills, deep red-brown loamy soils, with some occurrence of caliche (TWDB, 1973). A geologic map of Coke County is presented as Figure 3. The generalized stratigraphy of the Colorado River watershed is presented in Table 3 (BEG, 1999).

Permian formations located in Coke County were deposited as a result of a combination of an evaporating ocean and an influx of eroded material from an ancient mountain range to the west. The evaporating ocean principally left deposits of dolomite (magnesium, iron, and calcium carbonate), gypsum (calcium sulfate) and salt (sodium chloride) as part of the lithologic units. After deposition and burial of Permian–aged formations, naturally occurring hydrocarbons were also introduced from closely associated hydrocarbon source rocks into some of the Permian formations (Johnson, 2002).

Regional uplift associated with development of the Rocky Mountains and continued precipitation aided in the erosion of the Edwards Limestone creating the Colorado River Valley. Continued erosion along the Colorado River Valley progressed northwestward to expose the underlying Permian formations. This erosion of the Permian formations created an escape route for saltwater into the Colorado River. Aquifers of the Permian formations are in their infancy of development (10,000 to 20,000 years old) and continue to discharge saltwater and dissolved minerals into the Colorado River Valley. Specifically, the San Angelo sand has high concentrations of sulfate and moderate concentrations of chloride (Johnson, 2002).

The subsurface lithology was interpreted to a maximum depth of 97 feet below ground surface (bgs) based on boring logs from monitoring wells MW-01 through MW-18. The boring logs for each monitoring well are presented in Appendix B. The locations of the geologic cross-section lines completed across the Wendkirk Oil Field, are presented in Figure 2; and the geologic cross sections are presented as Figures 4 and 5. In addition to the geologic information, the cross-sections present the monitoring well completion details, depth to water, surface water elevation along the Colorado River, and location of the drainage features (i.e., Colorado River and creeks) within the Wendkirk Oil Field. The general surface lithology consists of alluvial sediments (fine grained to course sands) that are unconsolidated to loosely cemented. Outcrops of the San Angelo Formation bedrock occur across the Wendkirk Oil Field, typically along steep topographic changes. Outcrops also are located along the banks of the Colorado River. The San Angelo Formation lithologic data collected during the installation of monitor wells within the study area was consistent with the descriptions from published geologic reports. The San Angelo formation is part of the Pease River Group consisting of alternating beds of shale and sandstone. The San Angelo Sandstone outcrops in the study area, striking generally north-south and dipping west across Coke County at 15 to 20 degrees (TWDB, 1973). The San Angelo Sandstone consists of fine to course, well cemented sands. On the northern and western portions of the study areas, in the vicinity of MW-18 and MW-14, respectively, a clay stone (shale) overlies the San Angelo Sandstone. This unit acts as a confining layer for groundwater in the sandstone. This clay stone was also noted during the drilling of Monitor Well MW-6, where it is overlain by another sandstone unit. Some clay layers were encountered in the boring drilled in the study area; however, these were usually thin, discontinuous, and associated with the Quaternary alluvial deposits or with the weathering of the clay stone (shale).

3.2 Hydrogeology

Based on the October 2002, *Aquifers of Cook County, Texas* (Johnson, 2002), regional groundwater within the San Angelo Formation follows dip and trends west. Groundwater flow in the shallow groundwater of the San Angelo Formation; however, will follow the localized topography and is influenced by the presence of the Colorado River and smaller tributaries.

The Coleman Junction Formation, a limestone and shale formation of the Permian Wichita-Albany Group (BEG, 1976), is an artesian brine-bearing unit at depths of 200 to 300 meters (approximately 655 to 985 feet) that is commonly cited as a principal source of near-surface brine (BEG, 1990). The Coleman Junction, however, is beyond the exploration depth of airborne and ground-based geophysical instruments used in this study of the Wendkirk Oil Field. Brine within non-producing geologic units, such as the Coleman Junction Formation, can reach the near-surface environment through deep water wells and improperly plugged oil and gas wells reaching deeper strata (BEG, 1999).

Figure 5 presents the April 20, 2007, groundwater potentiometric surface map based on the data collected from the monitoring wells, water wells, and Colorado River. The groundwater elevations are provided in Table 2. Based on the groundwater elevation measurements from wells located on the south side of the Colorado River, groundwater flow is towards the north-northwest with a hydraulic gradient of 0.005 feet per foot (ft/ft). Data is limited on the north side of the Colorado River, therefore the groundwater flow direction and gradient could not be determined. However, the data collected from wells on the north side of the river indicates that the Colorado River does influence groundwater flow gradient and direction.

Literature shows that yields within the San Angelo Sandstone are typically less than 5 gallons per minute (gpm); however higher yielding wells are present north of the Colorado River and on or slightly down-dip of outcrops (i.e., points of recharge). Specific capacities of 0.03, 10, and 143 gpm per foot (gpm/ft) of drawdown have been recorded with the shallower windmill wells typically having a specific capacity of less than 1 gpm/ft (TWDB, 1973).

A review of the data collected during development and purging (Appendix A) of the eighteen groundwater monitoring wells located in the study area shows that half of the wells can be bailed dry, and all show significant draw-down during these activities. Using qualitative recovery data collected during well development activities at Monitoring well MW-10, a deeper well that does not go dry, it was estimated that the specific capacity is approximately 0.1 gpm/ft. This means that for every 1 gpm the well is pumped, the drawdown in the well will be 10 feet. Data collected at Monitoring Well MW-18 showed an estimated specific capacity of approximately 0.02 gpm/ft. This information agrees with the literature values presented by TWDB and indicates that wells within the study area are not good water producers.

Flow within the Colorado River varies based on the time of year. USGS data collected from 1980 to 2004 from the Robert Lee and Ballinger Stations indicate that daily mean stream flow increases during the summer with an average flow of approximately 111 cubic feet per second (ft^3/sec) at Robert Lee and 50 ft^3/sec at Ballinger and decreases in the winter with an average flow of approximately 42 ft^3/sec at Robert Lee and 6 ft^3/sec at Ballinger (BEG, 1976).

4.0 INVESTIGATION RESULTS

This section presents the analytical results and field measurements collected from the seasonal water monitoring and groundwater monitoring as well as the geophysical investigation results, and quality assurance information. These data were collected during the investigation activities in order to achieve the objectives discussed in Section 1.2.

4.1 Surface Water

The surface water analytical results from seasonal sampling events conducted during July 2006, August 2006, and April 2007 are presented in Table 4. The following sections discuss the results of the seasonal water monitoring.

4.1.1 Stream Flow and Gauging Measurements

Stream flow measurements were collecting on July 11, 2006, August 29, 2006, and April 18, 2007, at Colorado River segments 3 and 18. Stream gauging was conducted during April 18, 2007, at Colorado River segments 13, 14, and 15. The stream flow measurements were used to calculate the stream flow discharge rate, and the river gauging measurements were used to calculate the elevation of the river. The stream discharge rates and elevations are presented in Table 5.

Stream flow measurements collected on July 11, 2006, indicated that, at that time, the Colorado River could be a losing stream between segments 3 and 18, based on the discharge rate decreasing from 7.4 ft^3/sec at segment 3 to 0.0 ft^3/sec at segment 18. The August 29, 2006, measurements indicated that, at that time, the Colorado River discharge rate increased from 3.3 ft^3/sec at segment 3 to 12.6 ft^3/sec at segment 18. This may be attributed to increased runoff from tributaries and surface runoff into the Colorado River from a localized precipitation event that occurred on August 27 and 28, 2007. According to data recorded by the National Weather Service (NWS) from San Angelo, approximately 4 inches of precipitation fell in the area near the Wendkirk Oil Field during that time period. Stream flow measurements collected on April 18, 2007, indicated that the Colorado River returned to a losing stream between segments 3 and 18 based on the discharge rate decreasing from 3.2 ft^3/sec at segment 3 to 2.3 ft^3/sec at segment 18.

River elevations were calculated for stations RG-01, RG-02, and RG-03 based on the gauging measurements performed on April 18, 2007. Surface water elevations in the Colorado River are very similar to groundwater elevations in monitoring wells located near the river banks. Because surface water located in the Colorado River appears to be hydraulically connected to groundwater, the gauging data was used to assist in contouring the groundwater potentiometric map presented as Figure 4. A comparison of groundwater elevations from monitoring wells MW-18 and MW-08 to surface water elevations from river gauging stations

RG-01 and RG-02, respectively, indicated that groundwater flow was toward the river during April 2007. Therefore, the Colorado River appears to be a gaining stream between segments 13 and 15. A comparison of the groundwater elevation at monitoring well MW-07 to surface water elevation at river gauging station RG-03 indicates that groundwater flows away from the river toward MW-07 during April 2007. Therefore, the Colorado River appears to be a losing stream along segment 15. The groundwater elevations at water wells Milford-01 and Milford-02 indicate that the Colorado River appears to return to a gaining stream along segment 16. These conclusions will be verified by future seasonal sampling events.

4.1.2 Analytical Results

Figures 7, 8, and 9 depict the July 2006, August 2006, and April 2007 analytical results for calcium, chloride, sodium, sulfate, and field conductivity from samples collected from the Colorado River. As seen on the figures, the concentrations of chloride, sodium, sulfate, and conductivity were lower in August 2006 as compared to July 2006 and April 2007. The concentration differences are attributed to the August 27 and 28, 2006, precipitation event, which potentially diluted the analyte concentrations due to an increase in the volume of surface water discharged into the Colorado River relative to the volume of groundwater base flow. Also seen on these figures are increasing chloride concentrations from Colorado River segments 3 to 10. Chloride concentrations continued to increase after Colorado River segments 10 and 11 during July 2006 and April 2007, but decreased after segment 10 during August 2006. BTEX and TPH were not detected in any samples collected along the Colorado River. The only surface water sample locations that exhibited elevated calcium, chloride, sodium, and/or sulfate concentrations compared to concentrations in the Colorado River were springs 4314102 (Mays property, south of Colorado River), 4314104 (Milford property, north of Colorado River), and the SANCO quarry. Calcium was the only elevated target analyte at the SANCO quarry.

Outcrops of San Angelo Formation were observed along springs 4314102 (Mays property, south of Colorado River) and 4314104 (Milford property, north of Colorado River). Spring 4314102 consists of two separate branches which converge toward the Colorado River. Two samples, W-SG-4314102-01 (east) and W-SG-4314102-02 (west), were collected at the most upgradient spring discharge points. The results for sample location W-SG-4314102-01 indicated elevated salinity with higher concentrations of chloride, sodium and sulfate as compared to the Colorado River. The results for sample location W-SG-4314104 indicated elevated salinity with higher concentrations of sodium and sulfate compared to samples collected from spring 4314102 and the Colorado River. The highest concentrations of sulfate at a spring, as compared to surface water and groundwater analytical results, were observed at spring 4314104. The elevated sulfate concentrations at spring 4314104 may be attributed to the dissolution of gypsum that is present in the San Angelo Formation north of the Colorado River.

There were slight variations in analyte concentrations in water samples collected from May's Ranch Seep and May's Ranch Creek (upstream and downstream). The analyte concentrations at these locations were relatively the same as the Colorado River, but lower than the groundwater analyte concentrations in the Wendkirk Oil Field area.

The "one time" task to identify potential sources for elevated chloride concentrations north of Colorado River segments 7 and 8, based on December 2005 field screening results, was conducted during July 2006. Mr. Bob Blackwood, a relative of the property owner, granted TRC personnel access to the property to allow samples to be collected from surface ponds located north of segment 7. During an interview with Mr. Blackwood, he indicated that he was not aware of any oil and gas drilling on the property. A visual survey of the site was conducted and no evidence of historical or recent oil and gas activities was observed. There were a few noticeable barren areas (no vegetation and surface cover consisting of red soils), but the reason for these could not be determined. Surface flow from the barren areas drained into two round surface ponds from which field conductivity measurements were collected. The conductivity of the north pond was 618 micro-siemens per centimeter (µS/cm) and the conductivity of the south pond was 540 µS/cm. A surface water sample (W-O-01) was collected from the north pond and field tested for chlorides. The field chloride results for surface water sample W-O-01 was 74 milligrams per liter (mg/L). A water well (Tidwell) was located by TRC personnel on the adjacent property owned by James Tidwell, north of Colorado River segment 8 as illustrated in Figure 2. A sample could not be collected from the Tidwell water well because the windmill was locked down and no other access points to well casing were available.

4.2 Groundwater

The groundwater analytical results from groundwater investigation events completed during August 2006 and April 2007 are presented in Table 4. The following sections present the groundwater investigation results.

4.2.1 Groundwater Quality Parameters

The groundwater quality parameters including temperature, conductivity, pH, and turbidity were documented on the field sampling forms which are presented in Appendix A. Conductivity measurements ranged from 1,750 uS/cm to >19,999 uS/cm (i.e., over the range of the instrument) in monitoring wells and water wells during the August 2006 and April 2007 sampling events. The pH at Mays-01 was 5.84 on August 23, 2006 and 6.32 on April 9, 2007. The pH value at Mays-01 is lower than the range of 6.49 to 7.61 observed in the other monitoring wells and water wells during the August 2006 and April 2007 sampling events.

4.2.2 Analytical Results

Figure 10 presents radar graphs for monitoring wells, water wells, and produced water collected at the Salmon #1 SWDF to depict the concentrations of chloride, calcium, sulfate, and sodium. The radar graphs trending to east (sulfate) may be indicative of groundwater dissolution of the local gypsum-rich geologic units (Blaine Formation) and suggest naturally-occurring salinity. Radar graphs trending to the north (calcium) may indicate groundwater dissolution of calcium carbonate from dolomite or calcium carbonate cemented sandstone and suggest naturally-occurring salinity. Radar graphs trending to the south (sodium) and west (chloride) appear to indicate impacts from oil and gas exploration and production. Based on these general interpretations, radar graphs for a majority of the monitoring wells (MW-01, MW-04, MW-05, MW-06, MW-10, MW-11, MW-12, MW-16, MW-18, and Mays-01) south of the Colorado River indicate impacts from oil and gas activities. Radar graphs for monitoring wells MW-08 and MW-14, as well as water wells Milford-01 and Milford-02 north of the Colorado River, indicate groundwater dissolution of the local gypsum-rich formations in that area.

Chloride concentrations in groundwater are presented on Figure 11. Analytical results from the July 2006, August 2006, and April 2007 sampling events were used. The chloride isocentration map depicts an area with elevated chloride concentrations beginning near monitoring well MW-18 and continuing northeast to MW-11. The highest chloride concentrations, 29,000 mg/L and 27,900 mg/L, were detected at monitoring well MW-18 and the Mays-01 water well, respectively. The extent of the elevated chloride concentrations has not been delineated to the southeast and southwest of MW-18. Elevated chloride concentrations were also detected at monitoring well MW-01. The extent of the elevated chloride concentrations has not been delineated to the northwest of MW-01 and north of MW-16. Based on available information, it is not known if two separate chloride plumes exist, one located south of the Colorado River along segments 13 and 14 and another located south of the Colorado River, near MW-01/spring 4314102 (Mays property, south of Colorado River).

Chloride-to-sulfate ratios near or higher than 1 may indicate preferential chloride contributions from produced water, releases from oil field activities, or from water migrating upward from deeper pressurized saline zones. The chloride-to-sulfate ratios calculated for groundwater samples collected from the monitoring and water wells at the site vary widely. Analytical results from the July 2006, August 2006, and April 2007 sampling events were used to create Figure 12. As seen on Figure 12, an area of elevated chloride/sulfate ratios is centered around water well Mays-01. The chloride-to-sulfate ratio at Mays-01 was 19.6 in August 2006 and 17.2 in April 2007. The next highest chloride-to-sulfate ratios of 6.9 and 6.3 were located at monitoring wells MW-11 and MW-18, respectively. Because the extent of the elevated chloride concentrations has not been delineated to the southeast and southwest of MW-18, the map depicts the chloride-to-sulfate ratio contour line extended to monitoring well MW-06.

The highest chloride-to-sulfate ratios were observed at water well Mays-01, which were approximately 3 times higher than the next highest chloride-to-sulfate ratios observed at monitoring wells MW-11 and MW-18 located downgradient from Mays-01. Monitoring well MW-17 was installed upgradient from Mays-01 at a former pit location (based on historical aerial photographs). During April 2007, the chloride concentrations increased to 3,870 mg/L and 27,900 mg/L and chloride-to-sulfate ratios increased to 1.5 and 17.2 at MW-17 and Mays-01, respectively. This data suggests the source area is located between MW-17 and Mays-01. Additionally, the elevated concentrations of calcium, chloride, and sodium detected in Mays-01 compared to other wells and the produced water sample suggest that the water well was potentially used as a disposal well.

4.3 Produced Water

The RRC conducted a review of RRC electronic files on May 30, 2007, and determined that current oil production in Wendkirk Oil Field area is from the Wendland Cross Cut and the Wendkirk Cisco formations. Produced water from the wells completed in these formations is injected into the Wendkirk Cisco formation at Salmon #1 SWDF. The analytical results from produced water collected from the aboveground storage tanks at the Salmon #1 SWDF are presented in Table 4. The SWDF analytical results indicate elevated concentrations of calcium, chloride, sodium, and total dissolved solids (TDS). Over ninety percent of the TDS is comprised of chlorides and sodium. Sulfate concentrations are relatively low compared to surface water analytical results for the Colorado River. Based on the analytical results, the chloride-to-sulfate ratio for the produced water is 401. This data demonstrates that elevated chloride-to-sulfate ratios may indicate preferential chloride contributions from produced water (BEG, 2007). Additionally, the concentrations of calcium and sodium were elevated compared to other water samples collected from the area.

The majority of the TDS concentration (138,000 mg/L) for the produced water sample was compromised of chlorides (89,900 mg/L) and sodium (38,300 mg/L), therefore, water samples collected in the Wendkirk Oil Field area with elevated chloride and sodium concentrations likely indicate sources from oil and gas activities. Figure 13 depicts groundwater chloride concentrations versus TDS concentrations for the produced water and groundwater samples. Groundwater samples collected at monitoring well MW-18 and water well Mays-01 are most similar to the produced water sample, indicating conditions at these wells are influenced by former oil and gas production activities.

4.4 Quality Assurance

The analytical results were reviewed by TRC's quality assurance/quality control (QA/QC) chemist for compliance with the criteria presented in the QAPP. The QC review is provided in Appendix F. QC data associated with laboratory measurements indicate that measurement data are defensible and that measurement data reliability is generally within expected limits of sampling and analytical error given the data interpretation issues identified in the evaluation. The data user is advised of the following specific issues which are presented in the QA/QC reports:

July 2006 Seasonal Sampling

- Based on MS/MSD recoveries, the reported concentration of sulfate in sample W-RS-03 includes a slight high bias that may extend to other samples collected as part of this event.

- Based on MS/MSD recoveries, the reported concentration of sodium in sample W-RS-15 includes an extreme low bias and should not be used for decision-making purposes. It should also be noted that the low sodium bias is likely only to apply to sample W-RS-15 since other samples in this project were analyzed as MS/MSD pairs for sodium and exhibit compliant recoveries.

- Based on field duplicate RPD values, reported results for chloride, sulfate, and TDS in sample W-WW-Milford-01 include excessive imprecision. The excessive variability is likely only to apply to sample W-WW-Milford-01 since other samples in this project were analyzed as field duplicate and exhibit compliant recoveries for chloride, sulfate, and TDS.

August 2006 Seasonal Sampling and Groundwater Investigation

- Based on laboratory notes regarding receipt temperature, reported results for all target analytes in samples W-MW-01, W-MW-02, W-MW-02-D, W-EB-8-30-06-01, W-TB-8-30-06-01, W-RS-10, W-Q-01, W-RS-09, and W-EB-8-30-06-02 are likely biased low.

- Based on multiple MS/MSD recoveries, reported concentrations of sodium in samples W-MW-07, W-WW-Milford-01, W-MW-01 include an extreme low bias and should not be used for decision-making purposes. It should also be noted that the low sodium bias may apply to other samples collected as part of this event and these results are also rejected.

- Based on field duplicate RPD values, reported results for chloride and sulfate in sample W-WW-Milford-01 include excessive imprecision. The excessive variability is likely only to apply to sample W-WW-Milford-01 since other samples in this project were analyzed as field duplicate and exhibit compliant recoveries for chloride and sulfate.

- Serial dilution results are likely indicative of excessive variability in reported results for calcium and sodium in sample W-MW-07.

- Post-digestion spike results may indicate a low bias for calcium and a high bias for sodium in sample W-MW-01. These biases may extend to other samples collected as part of this event.

April 2007 Seasonal Sampling and Groundwater Investigation

- Due to holding time exceedances, TDS results in samples W-MW-11, W-EB-4-19-07-02, and W-EB-4-19-07-03 likely include a low bias. All three samples were received by the laboratory the day after sample collection. Sample W-MW-11 had to be prepared and analyzed a second time due to results that were inaccurate. When the sample was prepared for the second analysis, it was out of hold time. Hold time for the sample expired April 20, 2007, and the sample was re-prepped on April 24, 2007. Samples W-EB-4-19-07-02 and W-EB-4-19-07-03 were prepared and analyzed once on April 27, 2007, which is one day past the hold time. There was no reason given by the laboratory for this hold time exceedance.

- Based on a serial dilution RPD value, the reported calcium result in sample W-MW-09 is indicative of excessive variability. This increased imprecision may apply to other samples collected as part of this event.

4.5 Geophysical Investigation

The BEG conducted borehole and surface geophysical measurements in and around the Wendkirk Oil Field area after the first groundwater investigation to better define the aerial and vertical extent and possible sources (e.g., pits) of groundwater salinization that was inferred from the BEG airborne geophysical survey. The elevated salinity in the area was confirmed with the groundwater and surface water sampling conducted during July 2006 and August 2006. Results from the geophysical survey were used to guide the second groundwater investigation, specifically to determine where additional groundwater wells should be placed to achieve the overall project objective. A copy of the report is included in Appendix D. The following conclusions were presented in the BEG report:

- Lateral ground-conductivity transects, borehole gamma and conductivity logs, and TDEM soundings supplemented airborne geophysical survey and water and monitor well data to further delineate shallow salinization in the Wendkirk Oil Field area and assist in determining additional monitor well locations.

- Ground conductivity transects parallel to the Colorado River, along a creek, and near a saline seep identified salinization boundaries and seven salinized areas in and near the oil field within the limited exploration depth of the ground conductivity instrument. Ground conductivity transects indicate no evidence of shallow salinization north of monitor well MW-2, east of monitor well MW-3, and northeast of monitor well MW-7. Analyses of water samples from the Colorado River and from shallow wells suggest oilfield sources of salinity where apparent conductivities, TDS concentrations, and chloride/sulfate ratios are high.

- Borehole gamma logs demonstrated consistent and distinguishable natural gamma count rates within alluvial (high count rates) and bedrock units of the San Angelo Formation (high rates in mudstone and low rates in sandstone). These logs refine key stratigraphic boundary picks based on borehole cuttings descriptions.

- Borehole conductivity logs showed a strong relationship between water salinity and measured conductivity. These logs identified subsurface salinized horizons in water wells and monitor wells in and near the oil field. Multiple salinized horizons interpreted above and below the water table in the Mays-01 well suggest salinization to depths of at least 28 meters (approximately 92 feet) near a former brine pit. In other logged wells, salinization is evident in alluvium and bedrock near the contact between the two.

- TDEM soundings complemented borehole logs by determining conductivity profiles to deeper depths than those reached in wells. These soundings identified a shallow conductive layer with an upper boundary at or above the Colorado River elevation that is correlatable across the oil-field area. This layer represents an upper saline groundwater zone that water analyses, borehole logs, and lateral conductivity transects suggest has a strong oilfield salinity component. TDEM soundings also identified a deeper conductive, salinized zone that is likely to have natural salinity sources. This zone is below the Colorado River elevation and is not a likely contributor to elevated Colorado River salinities in this area.

Based on the EM survey results, monitoring wells were installed in locations where elevated conductivity measurements were observed. Monitoring well MW-13 was completed between monitoring wells MW-08 and MW-09 to evaluate elevated groundwater conductivity recorded during lateral ground EM transect along the Colorado River near Indian Creek. Monitoring well MW-11 was completed just upstream of the confluence of May's Ranch Creek and the Colorado River to evaluate ground conductivity recorded during the lateral ground EM transect across and along May's Ranch Creek. Monitoring well MW-17 was completed south of Mays-01 to evaluate elevated ground conductivity recorded during lateral ground EM transects across a potential source (former oil field disposal pit). A monitoring well was proposed to be completed along May's Ranch Creek northwest of monitoring well MW-04 to evaluate elevated ground conductivity recorded during lateral ground EM transects along May's Ranch Creek. The potential source of the elevated conductivity was assumed to be from a former pit location that was observed in the January 1964 aerial photograph. A monitoring well could not be completed at this location due to limited access by heavy vegetation.

5.0 CONCLUSIONS

The following conclusions were made based on the data collected during Phase II investigation activities:

- Stream flow measurements indicate the Colorado River may fluctuate from being a gaining stream to being a losing stream. Data collected during April 2007 was used to evaluate what portions of the Colorado River are gaining versus losing. The Colorado River appeared to be a gaining stream between segments 13 and 15 based on a comparison of groundwater elevations from monitoring wells MW-18 and MW-11 and surface water elevations from river gauging stations RG-01 and RG-02. The Colorado River appeared to change to a losing stream along segment 15 based on a comparison of the groundwater elevation at monitoring well MW-07 to river gauging station RG-03. The groundwater elevations at water wells Milford-01 and Milford-02 indicate that the Colorado River appears to return to a gaining stream along segment 16.

- Groundwater on the south side of the Colorado River within the Wendkirk Oil Field area flows towards the river in a north-northwest direction with a hydraulic gradient of 0.005 ft/ft. Data is limited on the north side of the Colorado River, therefore the groundwater flow direction and gradient could not be determined.

- Surface water samples collected along the Colorado River provide no indication of specific source(s) of salinity located near the river. Salinity concentrations begin to increase after segment 7 and continue to slowly rise through segment 18.

- Elevated salinity observed near spring 4314102 (Mays property, south of Colorado River) suggests the potential for oil and gas impact at the western discharge point of the spring, especially due to the higher ratio of sodium and chloride versus calcium and sulfate. Additionally, elevated salinity was observed at monitoring wells MW-01 and MW-03 located southwest and east of the spring, respectively. The elevated salinity at spring 4314102 and monitoring wells MW-01 and MW-03 suggests the area is hydraulically connected.

- The results of the BEG geophysical investigation (lateral ground-conductivity transects, borehole gamma and conductivity logs, and TDEM soundings) further delineated shallow salinization in the Wendkirk Oil Field area. These combined data were used to better define the lateral and vertical extent of salinization. The ground-conductivity transects help determine the lateral extent of elevated salinity which was used to determine monitoring well locations that were installed during April 2007.

The ground-conductivity transects were effective in locating areas (i.e., monitoring wells MW-10, MW-12, and MW-18) with elevated salinity in groundwater. Vertical delineation of salinity was achieved using the TDEM soundings, which identified a shallow conductive layer with an upper boundary at or above the Colorado River elevation that is correlatable across the oil-field area. This layer appears to represent an upper saline groundwater zone that water analyses, borehole logs, and lateral conductivity transects suggest has a strong oilfield salinity component. TDEM soundings also identified a deeper conductive, salinized zone that is likely to have natural salinity sources. This zone is below the Colorado River elevation and is not a likely contributor to elevated Colorado River salinities in this area (BEG, 2007).

- Elevated salinity was observed in groundwater in the Wendkirk Oil Field area. The highest concentrations were observed south of the Colorado River beginning at monitoring well MW-18 and continuing northeast to MW-16, water well Mays-01, MW-05, MW-10, and MW-11. April 2007 chloride-to-sulfate ratios in this area vary from 3.2 at MW-12 to 17.2 at Mays-01. The chloride-to-sulfate ratios north of the Colorado River vary from 0.1 at Milford-02 to 1.0 at MW-08. The elevated sulfate concentrations north of the Colorado River appear to be attributed from the dissolution of gypsum that is present in the San Angelo Formation north of the Colorado River.

- Based on the groundwater flow direction and the groundwater analytical results, groundwater is likely contributing elevated salinity into the Colorado River between segments 13 and 15.

- Elevated concentrations of calcium, chloride, and sulfate, as well as the highest chloride-to-sulfate ratios were observed at water well Mays-01. This data suggests that the Mays-01 water well was potentially used as a disposal well or there is a source area nearby associated with historical oil and gas production activities. Another possibility is that the water well is a converted former oil well that intersected the Coleman Junction. Groundwater parameters collected at water well Mays-01 indicated pH levels lower than other wells sampled in the area. Water located in the Coleman-Junction formation is known to be corrosive. The lower pH values observed in Mays-01 may indicate the well is impacted by the Coleman Junction.

6.0 RECOMMENDATIONS

The following recommendations are based on the data collected during the Phase II investigation activities:

- Based on the data collected from wells within the Wendkirk Oil field area, groundwater impacted with elevated salinity is predominately located within the San Angelo formation which is composed of cemented sandstone and clay stone. Groundwater is sometimes located in the overlying alluvium which is hydraulically connected to the San Angelo formation; however, the saturated thickness of the alluvium is typically less than 5 feet. The depth to groundwater within the alluvium and the San Angelo formation ranges from approximately 15 to 65 feet bgs. Based on the depth to water and lithology, groundwater removal by pumping in the Wendkirk Oil Field would be the most effective BMP to reduce salinity entering into the Colorado River.

- In Order to properly design appropriate BMPs, aquifer parameters (hydraulic conductivity, specific capacity, etc.) will need to be determined. Specific capacity estimations will first be collected by performing step drawdown tests. Data collected from the step drawdown tests will determine the most appropriate aquifer testing method(s) to be used (i.e., slug testing or pumping tests).

- Install three additional monitoring wells to delineate elevated salinity in the Wendkirk Oil Field area. New monitoring wells will be installed between MW-16 and MW-1, southeast of MW-18 at an area of former well field operations, and southwest of MW-18 as access allows. The monitoring well to be installed between MW-16 and MW-1 will help determine if salinity concentrations at MW-1 are isolated or connected to the elevated salinity concentrations observed at MW-11. This information will direct how concentrations of elevated salinity in the vicinity of MW-1 are handled and will also assist in refining the site conceptual model. The well southeast of MW-18 will assist in determining if there are former source areas upgradient of MW-18 contributing to concentrations measured in that area. The remaining monitoring well southwest of MW-18 will refine the western boundary of the area of impact and will assist in determining where BMPs should be installed.

- Data collected during previous investigation activities at the site have indicated the highest salinity in groundwater is present at water well Mays-01. No information concerning the installation and construction of this well has been found. A thorough search of the RRC central files should be conducted to determine if Mays-01 is a water well which has been converted from an oil well that may be improperly plugged. Additionally, to better understand how concentrations measured in the well relate to the concentrations observed across the site, the well should be investigated using geophysical logging techniques (e.g., caliper test, resistivity, gamma, and down-hole camera) to determine the well construction. Based on the information obtained from this logging, discrete groundwater samples should be collected from different depth intervals within the well and analyzed for calcium, chloride, sulfate, sodium, and TDS.

7.0 REFERENCES

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APPENDIX A

FIELD FORMS

APPENDIX B

BORING LOGS AND WELL CONSTRUCTION REPORTS

APPENDIX C

LABORATORY ANALYTICAL REPORTS – DHL ANALYTICAL

APPENDIX D

BUREAU OF ECONOMIC GEOLOGY GEOPHYSICAL INVESTIGATION REPORT

APPENDIX E

SKG SURVEY REPORTS

APPENDIX F

ANALYTICAL DATA REVIEW/VALIDATION CHECKLISTS