ASSESSMENT OF OIL FIELD ACTIVITIES, NON-POINT SOURCE POLLUTION & WATER QUALITY IN THE SPRING CREEK WATER SHED & THE CITY OF EDMOND MUNICIPAL WELL FIELD

EPA FY-2002 319(h) PROJECT 8
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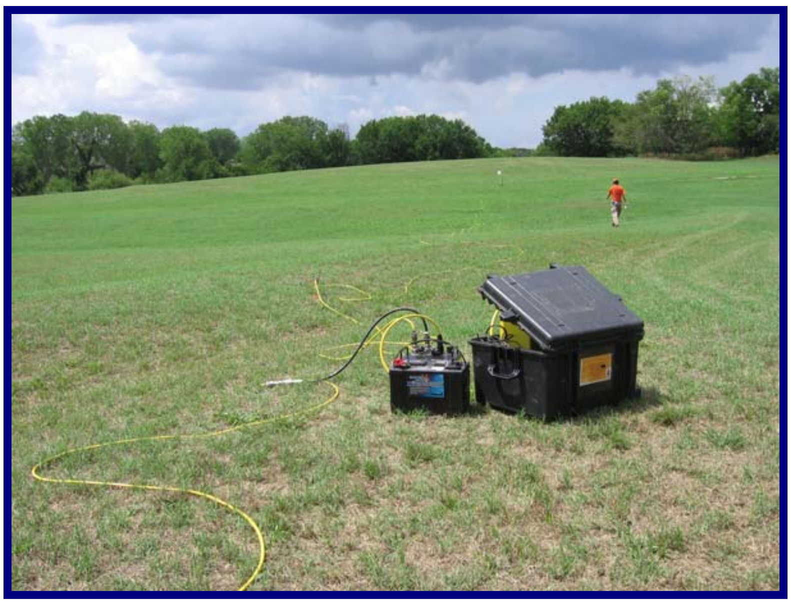

Prepared by:

Ground Water Protection Council

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DISCLAIMER

The interpretations and results presented herein are based on inferences from electrical or other measurements, public domain materials and ground water chemical data. The Ground Water Protection Council made a conscientious effort to ensure the accuracy of the report. However, the Ground Water Protection Council cannot and does not warrant or otherwise guarantee the accuracy or correctness of any interpretation or the reliability of the data obtained from, or furnished by other sources. The officers, agents and employees of Ground Water Protection Council shall not be liable or responsible for any interpretations and/or decisions based on data used in the production of this document.

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

TABLE OF CONTENTS (CONT.)

EXECUTIVE SUMMARY

BACKGROUND

Since 1987, homeowners in the Thunderhead Hills Addition in Edmond, Oklahoma have complained of elevated concentrations of saline water in their private potable water supply wells. Complaints received by the Oklahoma Corporation Commission (OCC) in the mid 1990's asserted that past oil and gas activity was the source of saline impact to the private water wells. In response to this problem, two studies were completed in 1997 and 1999. The findings of the studies presented differing interpretations for the cause of saline impact and the direction of saline migration.

As a consequence of the contradictions presented in the 1997 and 1999 studies, the Oklahoma Conservation Commission (OKCC) recognized the need to more thoroughly investigate the problem and contracted with the Ground Water Protection Council (GWPC) to conduct this study entitled *"Assessment of Oil Field Activities, Non-point Source Pollution & Water Quality in the Spring Creek Watershed and the City of Edmond Municipal Well Field."*

STUDY GOALS

The purpose of the study was to gather geophysical, geochemical and hydrogeologic data to:

- Determine the extent and movement of the saline plume relative to the study area; and
- Characterize the chemistry of impacted well water for comparison with identified potential causal saline sources; and
- Identify or eliminate specific sources of salinity.

STUDY METHODOLOGY

The methodology for conducting the study consisted of establishing and evaluating four elements:

- Land Use
- Hydrogeologic Setting
- Geochemical Framework
- Saline Plume Delineation

Land Use

The study area encompasses approximately 1,440 acres, which includes the Thunderhead Hills Addition and surrounding contiguous quarter sections of land; all of which lie within the Spring Creek watershed of the Deep Fork River Basin. More specifically the study area includes all or portions of Sections 29, 30, 31 and 32 of

Township14 North, Range 2 West of the Indian Meridian in Oklahoma County, Oklahoma.

Prior to development, native trees and grass, except for a forty-acre tract, which had been placed into crop production, characterized the study area. The Thunderhead Hills Addition was constructed over the footprint of historical oilfield production that was first established in the immediate area in 1943. Oil production operations included the injection of saltwater for secondary oil recovery beginning in 1953 and continuing until 1972.

Thunderhead Hills has been used for single family housing since 1973. At that time city utilities were not available to the subdivision. Consequently, homeowners had to rely on the use of domestic wells for a potable water supply and individual in-ground septic systems for sewage management. About sixty (60) percent of the residents have used water softeners to treat hard ground water produced from their wells.

Hydrogeologic Setting

The study area lies within the recharge area of the Garber-Wellington Aquifer (GWA), which is comprised of Permian-aged sedimentary rocks. Quaternary alluvium and terrace deposits overlie the GWA along creeks and river basins. The primary focus of this study was the Garber sandstone because to date saline impact to the study area has been confined to this stratigraphic interval. The depth to first ground water in the study area is approximately fifty (50) feet below land surface.

Geochemical Framework

For this study water samples were collected and analyzed from seven domestic water wells located within the area of known saline impact, one non-impacted domestic well, and the only producing oil well within the study area. Additionally, a brine solution of water softener salt was prepared and analyzed. The samples were collected and analyzed to evaluate geochemical mixing relationships and determine or rule out potential source(s) of salinization.

To compare the geochemical characteristics of the saline plume with potential saline sources, Bromide/Chloride (Br/Cl) ratios of freshwater and potential brine sources were used to develop mixing curves. This method was selected because Br and Cl tend to be conservative ions, meaning they generally do not react with aquifer rock minerals. As the result of these characteristics, the concentration of Br and Cl are affected only by dilution. Consequently, the ratio of Br/Cl derived from different saline sources will fall within ranges that allow the source(s) to be differentiated from each other, thus allowing for identification or ruling out of a suspected source.

Plume Delineation

To determine the configuration of saltwater plume the GWPC utilized the services of Professor Todd Halihan, Ph.D. with the Boone Pickens School of Geology at Oklahoma State University. To identify and delineate the plumes, Dr. Halihan used a technique called Electrical Resistivity Imaging (ERI). This technique induces a direct electrical current into the ground that, when properly measured, shows cross sections of the electrical properties of subsurface materials with depth. In addition, ERI data collected by John Harrington with the Association of Central Oklahoma governments (ACOG) was used. Use of the ERI data resulted in identification of four saline plumes (Designated A, B, C and D).

STUDY FINDINGS

Through integration of the four elements listed above the study was able to:

- Characterize subsurface characteristics of the study area that control plume distribution,
- Characterize the size, depth and relative movement of plumes,
- Characterize chemical relationships between saline impacted ground water and potential brine sources, and
- Determine past and present land uses to identify potential sources causing the saline impact in the study area.

Based on historical land use in the study area, four potential saline sources associated with the following activities were evaluated during this study:

- Agricultural Activities
- Road Salting/De-icing
- Oilfield Activities
- Domestic Wastewater Management

The study determined that the likelihood of past agricultural practices or road de-icing applications having an impact on ground water and being sources of salinization were remote.

The geochemical mixing relationships strongly indicate that the principal source of saline impact to domestic water wells in the Thunderhead Hills Additions is from the backwashing of individual domestic water softeners. Saline backwash is then transmitted to the subsurface via domestic septic systems. However, interpretation of data used to characterize the saline plumes suggests that at least one saline plume exhibits characteristics that suggest the source of salinization may be a combination of water softener backwash and oilfield brine. Consequently, additional work needs to be performed to evaluate this condition. Beyond the limits of the Thunderhead Hills Addition, the source of salinization is suspected to be associated with oilfield activities.

INTRODUCTION

The Greater Edmond Area was at one time occupied by two prominent oilfields, the first being the Edmond Field, which was discovered in 1930 and later, the West Edmond Field, which was discovered in 1943. While many of the wells associated with these fields have long since been abandoned, active production remains in certain areas.

Lands that were once utilized for agriculture and oil field exploration and production purposes are rapidly being developed for commercial, residential and other uses. The rapid pace of development and increase to Edmond's population has caused expansion into areas where oil and gas activities were at one time considerable, but to a limited extent, still remain. In addition, the increase in population has caused Edmond city officials to consider extending its present water supply well field into areas (including the study area) that may have been adversely affected by historical oil and gas activities. Unfortunately, most developers, property owners and others citizens are unaware of these conditions until considerable resources have been invested and negative impacts from an economic, health and environmental perspective have been realized.

The study area encompasses approximately 1,440 acres, which include the Thunder-head Hills Addition and surrounding contiguous quarter sections of land; all lying within the Spring Creek watershed of the Deep Fork River Basin. It includes all or portions of Sections 29, 30, 31 and 32 T14N, R02W, Oklahoma County, Oklahoma. The geographic extent of the study area is shown in Figure 01. The study area also lies within the boundaries of the "Bartlesville Sand Water Flood Unit" and the eastern extent of the City of Edmond municipal water well field overlaps its western boundary.

To date, the study area is the only portion of the Spring Creek watershed where suspected non-point source saline water has been identified in private domestic water wells. Ground water samples collected by the Oklahoma Corporation Commission (OCC) in May 1999 confirm that at least twenty-two domestic water wells in the Thunderhead Hills Addition have been degraded by saline water at concentrations exceeding the USEPA Secondary Maximum Contaminant Level (SMCL) of 250 mg/L for chloride in drinking water.

The presence of saline water has impeded further development of the Edmond municipal water well field immediately south of the study area in Sections 31 and 32, T14N, R02W. In addition, the City of Edmond derives a significant portion of its water supply from Arcadia Lake. The documented saline plume is thought to have the potential to "daylight" into tributaries of Spring Creek, which flows eastward and discharges into Arcadia Lake.

OBJECTIVES

The objectives of the project were to assess oil field activities and past land use to delineate the extent of saltwater intrusion and to identify or rule out source(s) of non-point source (NPS) pollution. These objectives were achieved using a combination of surface resistivity geophysics, geochemical fingerprinting (modeling), borehole geo-physics and hydrogeologic characterization.

HISTORICAL BACKGROUND AND PREVIOUS INVESTIGATIONS

Economic development in the area started with the discovery of oil reserves in 1943 by Harper & Turner Oil Company and the subsequent development of the West Edmond Field. In 1953, the OCC granted permission for the "South Bartlesville Sand Unit". This decision permitted oil producers to inject saltwater into the Bartlesville Formation to enhance oil recovery; a practice, which continued until 1972. According to Pedestal Oil Company, the current unit operator, all water flood distribution lines were flushed and capped as they were decommissioned.

In 1973, the Thunderhead Hills Addition marked the beginning of residential development in the study area. Since the subdivision was located outside the corporate boundary of the City of Edmond, Oklahoma at that time, the residents installed private domestic wells and septic systems to provide water and wastewater services.

According to documents prepared by the Thunderhead Hills Addition Homeowners Association the first indication of a saline problem wan noted in 1987 when the domestic well at 2901Timothy Way was found to have chloride levels in excess of 1700 mg/L. That same year, saline impacted water-bearing zones were noted on a driller's log in a borehole drilled in the SW, NW, SW, Section 29, T 14 N, R 2 W. Impacted zones in the borehole were reported from 40 feet to 57 feet, 85 feet to 92 feet, and 97 feet to110 feet. However, at that time the occurrence of saline water in the two boreholes were considered to be an isolated situation and no further action was taken.

In January 1991, a resistivity log survey recorded in a borehole drilled at 3000 Timothy Way indicated multiple saline-impacted zones over an interval from 90 feet to 160 feet. In response to this discovery and in light of previous information indicating the presence of saline impact, the City of Edmond Water Resources Department and the Garber-Wellington Association collected ground water samples from thirteen private domestic wells in April 1991. Four of the thirteen wells had chloride concentrations that were higher than the SMCL. Three saline impacted wells were located in close proximity to one another in the northern part of the Thunderhead Hills Addition.

Complaints filed with the Oklahoma Corporation Commission (OCC) in the mid-1990s against Pedestal Oil Company alleged that saline impact to ground water was associated with the company's oilfield activities in the area and that a saline plume was migrating below the surface. These complaints were referred to the Oklahoma County Health Department and were followed up through ground water sampling. A few examples, which alluded to the presence and migration of a saline plume are presented below:

- In September 1993 the domestic well located at 2901 Sherrywood Lane had measured chloride levels of 1110 mg/L. This same well exhibited chloride concentrations of 364 mg/L in the 1991.
- In January 1994, chloride levels of 880 mg/L were present in a shallow water well on the Pedestal Oil Company No. 1 Darwin lease located approximately 800 feet southeast of the original discovery well. In 1991, this well had chloride levels of 28 mg/L.

- Historic water quality records for the domestic water well located at 201 Stony Trail showed historical increases in chloride levels of 34 mg/L, 46 mg/L and 650 mg/L in 1984, 1991, and 1997, respectively.
- In 1996, the domestic water well at 408 Early Dawn Drive, in the extreme northeast corner of the Thunderhead Hills Addition, showed a chloride level of 1058 mg/L.

In 1997, the Thunderhead Hills Homeowners Association sought the expertise of Dr. Richard DeVries, a retired engineering professor and hydrologist from Oklahoma State University, to help determine the source of saline impact to domestic water wells in Thunderhead Hills. Based on the results of a 1997 sampling of twenty-eight wells in the addition and other available information, Dr. DeVries concluded that saline impact in the wells could be traced to the secondary oilfield recovery saltwater injection process. He also advised that migration of the saline plume was from northwest to the southeast.

The OCC Saltwater Contamination Task Force became involved with the problem in 1998 after the homeowners association made a presentation to the OCC Pollution Abatement Department asking that the complaint against Pedestal Oil Company be re-opened. The initial OCC response was to collect ground water samples from thirty-nine wells in May 1999. The task force findings were presented to the Thunderhead Hill Homeowners Association in August 1999, and suggested that the saline plume was migrating to the south-southeast at a rate of 100 feet/year. In a related letter, an OCC District 2 hydrologist stated, *"Unfortunately this data does not lead us to the source of contamination."*

Because the source of the saline plume was not identified in the OCC's 1999 sampling event it was not possible to develop a plan of action to prevent further ground water quality degradation. However, in recognition of the problem an interim action taken by the OCC and ACOG convinced the Oklahoma Water Resources Board (OWRB) to list the Thunderhead Hills Addition and portions of the immediately surrounding area in Appendix H, Title 785, Chapter 45 of the Oklahoma Water Quality Standards. This action required that the ground water zones that have been impacted by the saline plume be isolated (cased and cemented) in all future domestic wells drilled in the Thunderhead Hills Addition and immediately adjacent lands.

DATA ACQUISTITION

The following types and sources of data were acquired or reviewed to meet project objectives:

- Ground water chemical data, background information, case studies and investigations from published/unpublished reports, documents and papers;
- Acquisition of geophysical logs;
- Acquisition of OCC Form 1003-oil and gas well plugging records;
- Completion of eight Electrical Resistivity Imaging (ERI) surveys;
- Review and reprocessing of six ERI surveys performed by ACOG;
- Sample collection from selected domestic water wells; and
- Collection of brine source identification data.

The gathered information was used for subsurface hydrogeologic characterization and for chemical speciation of the ground water underlying the study area. The data was also used in delineating the areal extent of the saline plume(s), confirming and/or ruling out brine source(s), as well as developing recommendations to mitigate degraded ground water zones.

PUBLISHED AND UNPUBLISHED INFORMATION

Published and commercially available information was used to characterize subsurface geology and regional ground water quality, to document oil and gas activities, and to aid in identifying saline plume brine source(s).

Unpublished information included data acquired from previous OCC investigations, miscellaneous correspondence, historic ground water quality records and municipal well field geophysical logs.

GEOPHYSICAL LOGS

Geophysical logs from historic oil and gas exploration and production wells and municipal water wells were obtained from the Oklahoma City Geological Society log library, Riley's Electric Log Service and the City of Edmond Department of Public Works. Geophysical log suites included spontaneous potential/dual induction and gamma ray/compensated neutron-density surveys. Log interpretation was considered critical for developing a hydrologic conceptual model of the project area.

The oilfield well logs used in this study had recorded data across most the fresh ground water portions of the Garber Formation. This data was available because drilling standards at the time many of the logs were recorded did not require the setting of surface casing across shallow fresh water zones. Therefore, oilfield logs were used to identify the Garber-Wellington unconformity and to correlate stratigraphic sections of the Garber Formation. In addition to the use of oilfield well logs, geophysical logs recorded in municipal water supply wells were used to characterize subsurface stratigraphy of the Garber Formation.

ELECTRICAL RESISTIVITY DATA COLLECTION

An eight-channel Advanced Geosciences, Inc. (AGI) SuperSting resistivity meter was used to collect ERI data. In field application, cables, supplied with electrodes, were connected to the AGI meter through an electrode switchbox to collect and store subsurface electrical resistivity measurements. The depth of investigation is approximately 20% of the profile line length. The total length of each ERI survey line was generally around 1100 feet. Therefore the depth of investigation was approximately 220 feet.

Personnel from the Oklahoma State University School of Geology (OSU) performed a total of eight ERI surveys during this project. All work was performed under the supervision of professor Todd Halihan, Ph.D. The OSU surveys were located to the north, east and south of the Thunderhead Hills Addition (refer to Plates 01 and 02). The locations of the ERI survey lines were chosen based on the presence of known or suspected conditions, which could have played a roll in causing salinization of ground water in the study area, and to characterize background (un-impacted) ground water conditions. Another factor, which influenced the selection of ERI survey line locations was the presence of buried utilities. For example, the presence of buried utilities made it impossible to collect ERI data along a north-south line to the west of Thunderhead Hills.

Locations and orientations of the OSU ERI survey lines are shown in Plates 01 and 02, as well as Figure 02. Survey line length, line quality, line orientation and statistical evaluation of data quality are summarized in Table 1.

Six ERI survey lines were also available for review and interpretation through a collaborative project between the GWPC and ACOG. The ACOG data consisted of two east-west ERI survey lines, one north-south line and two detailed profiles within the Thunderhead Hills Addition. In addition, a common line (GWPC line TH. H; ACOG line THH 3) was recorded parallel to the northern Thunderhead Hills subdivision boundary line for use as a comparison between standard ERI data collection and processing method employed by ACOG and the OSU proprietary method. The locations of the ACOG survey lines are also shown in Figure 02 and Plate 01.

WATER ANALYSES AND BRINE SOURCE IDENTIFICATION

The 1999 OCC ground water data set was used to characterize ground water chemistry and aid in delineation of the saline plume. The data was evaluated and interpreted using hydrochemical methods developed by Whittemore (1995) to identify and rule out possible source(s) of saline impact. The Oklahoma Statue University Oklahoma Cooperative Extension Service located in Stillwater, Oklahoma analyzed all water samples collected by the OCC. *AquaChem,* a commercially available chemical evaluation software program was used for data validation and analysis.

The ground water data sets collected in 1991 by the City of Edmond Water Resources Department and the Garber-Wellington Association, and data collected in 1997 by the Oklahoma County Health Department were proved to be useful in evaluating the historical development of the saline plume(s).

While helpful in delineating the areal extent of the saline plume(s), the 1999 OCC ground water chemical data set did not include analyses of bromide (Br), which, according to Whittemore (1995), is a useful element for identifying sources of saline impact. To augment the OCC data, ground water samples were collected from selected domestic wells for the analysis of sodium, chloride and bromide, nitrate and phosphate.

To confirm or rule out any suspected brine source, it was necessary to evaluate the ground water geochemical mixing relationships. To accomplish this task, knowledge of the chemical composition of each end member used in the mixing equation is required. To satisfy this requirement for evaluating the potential oilfield brine source, a sample of produced water was collected from the only actively producing well in the study area, the Pedestal No.1 Darwin, located in the NW/4, SW/4 of Section 29-T14N-R2W. OCC field personnel witnessed collection of the sample. Other chemical analyses representative of oilfield brines for wells located in Sections 28, 29, 31 and 33 of T14N-R2W were obtained from the published literature (Parkhurst, Christenson, 1987) and past OCC sampling events. The wells sampled and the formations analyzed are summarized in Table 2.

To evaluate the possibility of road deicing salt or septic tank effluent as brine sources, a sample of Morton Salt pellets used in water softeners was obtained from the residence at 3004 Timothy Way. Because both these potential sources are predominately the result of halite dissolution Br/Cl ratio overlaps can occur. However, Panno and others (Panno et al., 1999) found that Br/Cl fingerprinting of septic effluent can be successfully isolated from road deicing salt by using the geochemical relationships between other chemical indicators: K^{1+}, Ca^{2+}, Mg^{2+}, NO_3^{1-} and PO_4^{2-}. Therefore, a saline solution was prepared from the salt pellets at Oklahoma State University's School of Geology laboratory for the analysis of sodium, chloride, bromide, fluoride, nitrates and phosphates.

DATA VALIDATION

A conscientious effort was made to ensure that all data used in this study was reliable and reasonable. The techniques used to validate each grouping of data are presented below.

GEOPHYSICAL LOGS

Techniques used to determine if geophysical logs used in this study were reasonably accurate and reliable followed a method adapted from Schultz (1993). This method included:

- Examination of the log header, calibration data, repeat section, scale and remarks information.
- Identification of any reported or suspected operational problems, verification of measurement scales. If necessary, log scales were calibrated to conform to known formation data values.
- Examine shape and character of the recorded curves to ensure they were commensurate with the type of device generating the measurements.

ELECTRICAL RESISTIVITY DATA

The first step in validating the ERI data collected during this study was to review the acquisition algorithm measurements, because they define the data set used to generate the ERI profile. Several factors were evaluated, including signal quality, resolution with depth, and ambient noise interference.

OSU personnel working on the project used the Halihan-Fenstemaker (HF) method process ERI data. The HF processing algorithm is a proprietary data acquisition array developed at Oklahoma State University, and is one of the most advanced high-resolution ERI data processing methods available. The ERI data collected by OSU for this project was performed using a double measurement protocol, which means that a measurement error was computed for each data point collected. As part of this Quality Assurance/Quality Control (QA/QC) protocol, data values having a repeatability error of greater than 5% were eliminated prior to conducting inversion processing. In addition, a filter was applied to remove abnormal “noise” spikes in the data.

After processing, the ERI data was imported to an inversion-modeling program, which was used to develop an apparent resistivity pseudosection to match the data collected in the field. The inversion process results in the production of a two-dimensional subsurface geo-electric cross section that shows vertical and lateral changes in resistivity along the ERI survey line as a function of depth.

Statistical analysis of the inversion modeling was performed using the root mean square (RMS) method. This method, also known as the quadratic mean, is commonly used to analyze the magnitude of varying quantities. Because resistivities vary laterally and vertically along an ERI line, this method was used to check the inversion process’s ability to replicate data collected in the field. The RMS is the difference between successive inversions and the measured data reported as a percentage. Typically, as the RMS percentage decreases, the precision of the inverse model to represent measured apparent resistivity field values increases.

VALIDATION OF WATER CHEMICAL DATA

Water quality data validation was accomplished by computing the cation-anion balance for each laboratory record. Because water containing dissolved ions must be electrically neutral, use of this method as a validation tool is recognized as a good indicator of data reliability. The cation-anion balance is expressed as a percentage. A margin of error ±5% is typically deemed acceptable since analytical methods used to determine ion concentrations are generally incapable of yielding results with any greater precision (Hounslow, 1995).

For water samples where a limited number of ions were analyzed, a cation-anion balance approach could not be used for validation. Under these circumstances a conscientious effort was made to ensure that samples collected in the field were as representative of natural conditions as possible by monitoring pH, temperature, and electrical conductivity values in the field. Water samples were collected only after it was determined that these readings had stabilized, with no greater than +/- 10% error in a specific reading for three consecutive readings.

DATA EVALUATION

SOURCES OF SALINIZATION

Present and past land use suggested the potential causes of shallow subsurface salinization included past agricultural practices; dissolution of road deicing salt; fresh water mixing with deeper formation brines; water softener discharge from septic systems; and oilfield activities.

Potential oilfield sources included brine infiltration beneath historic evaporation pits; leaking or improperly plugged oil and gas wells; and leaky injection wells/distribution piping associated with the water flood project (refer to Figure 03, Plate 02).

As explained below, the likelihood that past agricultural practices, road deicing applications or mixing with deeper formation connate water were sources of salinization was considered remote.

Agricultural Practices

Salinization of ground water from agricultural activities is usually associated with irrigation, animal waste lagoons or the application of commercial chemicals. Placing land into crop production and/or poor irrigation practices can concentrate salt in the soil profile, which could eventually infiltrate and degrade ground water quality. Land conditions most susceptible to deterioration by salt accumulation are poorly drained, high clay content soils in areas where shallow ground conditions (depth to ground water is less than twenty feet) exist.

Review of the Natural Resources Conservation Service (NRCS) publication *Soil Survey of Oklahoma County, Oklahoma* and the Oklahoma Water Resources Board (OWRB) on-line water well record database indicate a thin veneer (average 20-40 inches) of well-drained, sandy loam soil is ubiquitous over the study area and depth to first ground water is approximately 50 feet below land surface. Based on historical aerial photographs taken from 1950 through 2003, the land surface prior to residential development, was characterized by native tree and grass cover, except for approximately forty acres located in the NW/4, NW/4 of Section 29-T14N-R2W. This forty-acre tract appeared to have been used for crop production. Based on published soil texture data and the minimal acreage dedicated to crop production, agricultural practices were considered an unlikely or, at best, minor salinization source.

Road Deicing Salt

Deicing and sanding of bridges and highway overpasses is a winter road maintenance priority in Oklahoma. Potential designated snow routes in the study where deicing would most likely occur within the study area included Edmond Road (East 2nd Street), which borders Thunderhead Hills on the south, and North Coltrane Avenue, which borders Thunderhead Hills on the west. Because winters are generally mild in Oklahoma road deicing is rarely necessary, but if deicing of roads is required, it does not occur for extended periods of time (i.e. days or weeks) nor across large areas. Furthermore, observations of the ERI data indicate that surface runoff from these roads cannot account for the observed saline plume distribution. Therefore, deicing salt was not considered to have been a source of salinization.

Upwelling of Saline Water

The State of Oklahoma requires oilfield drilling and production operations to be protective of Underground Sources of Drinking Water (USDW). A USDW is defined as any subsurface formation that contains ground water having a Total Dissolved Solids (TDS) concentration less than 10,000 mg/L. A map of the elevation of the Base of the USDW in Oklahoma County (Figure 04) constructed from electric logs (Roberts, 2001) shows the depth to this horizon averages 765 feet. This depth is more than 550 feet below the deepest domestic well drilled in the Thunderhead Hills subdivision. This combined with a well-documented downward, vertical hydraulic flow direction (Parkhurst, Christenson, Scott and Breit, 1993) within the GWA makes the likelihood that upwelling and mixing of deep formation brines with shallow fresh water zones a highly improbable condition.

Septic Tank Effluent

Water for used for consumption and irrigation in the Thunderhead Hills subdivision has always been provided by shallow, privately-owned domestic water wells. Each property owner also has a private septic system for treating wastewater. Additionally, sixty percent of the residents in Thunderhead Hills own water-softening units to control water “hardness”. The insert in Figure 03 shows the locations of homes and/or lots where a water softener is being used to treat well water. When a water-softening unit is in operation, periodic flushing of the system is necessary. The resulting effluent is discharged directly into the septic tank for distribution to the septic absorption field. Over time, the discharged dissolved rock salt effluent has the potential to reach and elevate sodium and chloride concentrations in the ground water. The use of brine solutions in household water softeners can elevate sodium and chloride concentrations in septic system effluent to levels measured in thousands of milligrams per liter (Panno, 2005).

A typical residence consumes an average of 100 gallons of water per person per day for household activities. Consequently, for a family of three or four with moderately hard water, a water softening system would use approximately 1.8 Kg of sodium chloride (NaCl) per day (manufacturer’s recommended use). This daily amount computes to be 600 Kg of dissolved salt that is released to surface and ground water resources annually (Panno, 2006). The cumulative effect of water softener cycling thus provides a plausible rationale for considering water softener effluent as a potential salinization source within the Thunderhead Hills subdivision.

Oil & Gas Activities

Oil & gas activities in the study area date back to 1943, some thirty years prior to development of the Thunderhead Hills subdivision. The justification for considering oilfield activities to be a possible source of salinization was based on the following:

- Oil production in the East Edmond Field was first discovered in 1943. Surface casing in the oil wells generally did not extend below 200 feet in a well bore. This depth corresponds closely to the maximum drilling depths of most of the domestic water wells.

- Prior to the establishment of construction standards and land restrictions in the mid-1960s, a common oil industry practice was to dispose of high-chloride brine generated from oilfield activities in unlined evaporation pits.
- Secondary oil recovery operations using saltwater injection began in 1953 and continued until 1972.
- Review of OCC Form 1003-Plugging Records suggests that some abandoned oil wells and boreholes may have been plugged using standards that were less protective of the environment than current plugging requirements.

HYDROGEOLOGIC SETTING

The hydrogeologic units underlying the study area comprise the GWA, which consists of Permian-aged sedimentary rocks. Quaternary alluvium and terrace deposits overlie the GWA along creeks and river basins (Novell, 1995, Parkhurst et al, 1989). The Permian Garber Formation was the primary focus of this project, because ground water salinization within the Thunderhead Hills subdivision and immediately adjacent lands was confined to this geologic interval.

The Garber Formation is predominantly comprised of very fine to fine-grained sandstone that is typically massive to cross-bedded. Locally, sandstone layers are interbedded with siltstone, shale and clay. Quartz makes up 65%-82% of the rock matrix and illite (the predominant clay mineral) comprises between 9%-22% of the matrix (Parkhurst, Christenson, Breit, 1992). Other minerals that are present in the rock matrix include plagioclase, dolomite, kaolinite and hematite, each averaging from 3% to 5% of the total composition. Ground water produced from Garber sandstone in the study area is generally of good quality, is of the Calcium-Magnesium-Bicarbonate (Ca-Mg-HCO_3) type, and is commonly used for municipal and domestic supplies (Roberts, 2001).

The United States Geological Survey (USGS) subdivided the GWA into *"geohydrologic"* zones on the basis of shaliness and variations in major ion chemistry (Parkhurst et al., 1989). Studies suggest that shallow and deep reaches of the GWA exhibit both confined and unconfined conditions. Dominant water types in the GWA range from Ca-Mg-HCO_3, most common in the shallow zones in the area of recharge, to Sodium Bicarbonate (Na-HCO_3) in the deeper ground water zones (Paxton, Roberts, and Sahai, 2007).

Available oilfield well control and municipal water well logs were utilized to characterize and delineate the regional structural and stratigraphic relationships observed in the Garber Formation underlying the W/2 of T14N-R2W; all of T14N-R3W; the N/2 of T13N-R2W and the N/2 of T13N-R3W, Oklahoma County. Based on this work the Garber Formation thickness was determined to average 220 feet within the study area. East of the study area in eastern Oklahoma County, the Garber Formation pinches out at its erosional contact with the underlying Wellington Formation. To the west it thickens to approximately 350 feet where it subcrops beneath the Hennessey shale. A regional structure elevation map, constructed on the Herington Lime marker, (Plate 03) shows that the base of the GWA dips gently to the west at an average rate of 50 feet/mile. The Herington Lime marker marks base of the Wellington Formation.

Electric well log signatures and zone-specific ground water chemical data were used to distinguish between the Garber Formation and underlying Wellington Formation, and to characterize the geologic and hydraulic conditions that control distribution of saline impact.

Garber-Wellington Contact

The contact between the Garber and Wellington Formations (Plates 04 and 05) was identified using well logs to evaluate changes in lithology (generally more shale and siltstone in the Wellington), resistivity (decreased shale resistivity in the upper part of the Wellington) and ground water type (Garber sandstones are typically Ca-Mg-HCO_3 water bearing zones, Wellington sandstones are generally Na-HCO_3 water bearing zones). The Garber-Wellington contact was established previously (Roberts, 2001; Paxton, Roberts, and Sahai, 2007).

Subdivision of the Garber Formation

Based on sandstone log-curve characteristics (Wilson, Nanz, 1959) and local shale markers, it was possible to group the Garber Formation into three major stratigraphic electro-facies units, the Garber “A”, Garber “B” and Garber “C” (Plates 04, 05).

No attempt was made to subdivide the Garber “A”, because log data was generally not recorded across this interval and the scarcity of continuous shale markers within this unit made it difficult to correlate between zones over distances greater than 0.5 mile.

The Garber “B” unit was subdivided into two subunits designated “B-1” and “B-2”. The stratigraphic subunits maintained a relatively constant thickness across the study area. Well log curves within the sand packages were characterized by blocky and blocky with fining upward patterns having sharp basal contacts with underlying clay or shale. The log-curve shapes recorded in wells within the study area were similar to gramma ray profiles recorded at Garber outcrops in Cleveland County, Oklahoma, which were interpreted to have been deposited in fluvial depositional systems (Paxton, Abbot, Nick, Gromadzki, et al, 2005). Sandstone percentage maps (Plate 06, Plate 07) and meandering stream relationships discussed by Swanson (1976) allowed an interpretation of fluvial trends based on a predictable correlation between sand thickness and channel meander lengths. The sandstone percentage maps were constructed by establishing clean sand and shale baselines using the gamma-ray log curve. The gamma-ray value representing 40% of the difference between the respective baselines was used as the clean sand cutoff point. Map areas shown on Plate 06 and Plate 07 where the sand percentage value is greater than 75% were interpreted as representing point bar deposition.

Based on log curve characteristics the Garber “C” unit was interpreted to represent deposition in a fluvial-deltaic environment. Mapping of the unit revealed the presence of a lobate-shaped depositional pattern. However, the Garber “C” unit thickness was determined to be thin in the study area. Furthermore, the saline plume(s) had not impacted this stratigraphic interval. A sandstone percentage map of the Garber “C” unit was not presented with this report.

The geologic constraints influencing the migration of the saline plume(s) discussed herein are consistent with previous studies previously cited in this report. A conventional ground water surface gradient (elevation) map, typically constructed to establish hydraulic control, was not prepared because reliable static water level data could not be obtained from wells in the study area. The lack of reliable ground water level data was due to the fact that wells were completed at different depths, and two or more ground water-bearing zones were typically commingled in a single well. These conditions were verified by driller's logs which documented that domestic wells in the Thunderhead Hills Addition were completed at depths ranging from 120-220 feet after penetrating multiple saturation zones and reported well annular spaces were backfilled with gravel from total depth to the surface during well construction.

To evaluate hydraulic direction of ground water movement and saline plume migration, a structure (elevation) map constructed on the Base of the Garber "B" unit was prepared. Mapping of this horizon was chosen for the following reasons: 1) The Garber "B" is under semi-confined aquifer conditions due to the presence of clay and shale above and within the stratigraphic interval; 2) there was sufficient subsurface data to allow mapping of this horizon over the entire study area; 3) the geologic markers used to define the boundaries of this stratigraphic interval were easily identifiable; and 4) the Garber "B" subunits maintained a relatively constant thickness across the study area.

The Base of the Garber "B" structure map shows that ground water flow across the study area is toward the west-southwest (Plate 08). The combined local geologic and hydraulic controls across the study area are shown in Figure 05.

DATA INTERPRETATION

GROUND WATER CHEMISTRY

In general, ground water chemical data revealed that chloride levels ranged from 30 mg/L to 1,258 mg/L in the study area. A summary of the analytical results and statistical analyses are presented in Table 3 and Table 4, respectively.

Eighty-five percent of the domestic wells within the Thunderhead Hills Addition were sampled by the OCC in 1999. Samples were analyzed for the major cations and anions plus electrical conductivity (EC), TDS and hardness. Of the 1999 data set, six water samples were rejected as being non-representative of natural aquifer conditions because the samples were collected downstream of water softening systems. Two other water samples were eliminated because they were collected from wells completed in the underlying Wellington Formation, as demonstrated by their Na-HCO_3 water type.

Evaluation of the spatial distribution of the 1999 chemical data resulted in identification of an area covering approximately the northwestern one third of the Thunderhead Hills subdivision where the most elevated TDS (> 1000 mg/L) and chloride (> 250 mg/L) concentrations were present. To understand why elevated TDS and chloride concentrations seemed to be most prominent in this area, reference was made to a paper written by (Richter and Kreitler,1993) who studied saline water intrusion into fresh water aquifers along the Gulf Coast. Their ground water mixing studies documented that when saline water intruded a fresh water aquifer, ion exchange would occur whereby sodium was removed from solution and calcium was released from mineral exchange sites. Other studies by (Cates, Knox, and Sabatini, 1996) revealed that ion exchange processes under similar conditions can also retard the transport of sodium, resulting in the development of a “hardness halo” at the edge of the saline plume(s).

To determine if similar ion exchange conditions might be occurring in the Thunderhead Hills Addition, Ca/Na and Na/Cl ratio maps were prepared (Figures 06, 07). Both maps show that relatively lower Na/Cl ratios are present along a well-defined sinuous band of high Ca/Na ratios. These maps therefore suggest the presence of a northeast-southwest trending “hardness halo” that is similar in nature to that described by Cates, Knox, and Sabatini (1996).

To further evaluate ground water mixing relationships, Stiff diagrams and Schoeller plots were generated using the 1999 OCC chemical data (Figures 08 and 09). The Stiff diagrams show that fresh, un-impacted Garber ground water within the study area is predominately a Ca-Mg-HCO_3 type. Overall, five distinct Stiff diagrams and Schoeller plot patterns were identified (Figures 08 and 09) that indicated the presence of a gradational shift from fresh ground water conditions to progressively more saline conditions within the Thunderhead Hills subdivision. Mapping of ground water hydrochemical facies (i.e. water types) (Figure 10) further indicates that chloride becomes a dominant anion species in about the northwestern one third of the Thunderhead Hills subdivision. The Hydrochemical Facies Map also shows that the contact between the Ca-Mg-HCO_3-Cl waters (depicted by light green in Figure 10) and Ca-Mg-Cl-HCO_3 waters (depicted by orange in Figure 10) roughly corresponds to the “hardness halo” shown in Figures 06 and 07. Identification of this chemical relationship helped to place boundary conditions on the portion of Thunderhead Hills that was most affected by saline impact.

HYDROGEOLOGIC CONCEPTUAL MODEL

A hydrogeologic conceptual model was developed based on analysis of subsurface geophysical well log data, and studies performed by Paxton, Roberts, and Sahai (2007). The model incorporates geologic and hydraulic information, geophysical log signature characteristics and water chemistry.

Mapping of subsurface hydrogeologic conditions (Plates 05, 06, 07 and 08) indicate that movement of ground water through the aquifer is primarily influenced by the following two controls:

- Geologic controls (i.e. changes in lateral and vertical distribution of lithofacies); and
- Hydraulic controls (i.e. changes in head elevation).

In many investigations, the importance of the geologic framework its impact on lateral and vertical movement of ground water (and therefore saline impact) is sometimes overlooked. In this study a conscientious effort was made to understand the distribution of lithofacies and how that could influence the migration of saline plume(s).

The heterogeneous nature of fluvial depositional systems is generally characterized by vertical and lateral shifts in rock texture represented by changes from coarse-grained to fine-grained lithofacies (i.e. from sandstone to siltstone to shale). Significant differences in hydraulic conductivity values occur as the result of these textural changes in the rock fabric, with the greatest hydraulic conductivity (permeability) values being associated with the coarse-grained lithofacies and the lowest values being associated with fine-grained lithofacies.

Geologically speaking, the coarse-grained lithofacies identified from geophysical logs recorded in the shallow subsurface portions of the study area were interpreted as point bar deposits. Point bar deposits provide preferred migration pathways for the movement of ground water and thus a saline plume. Where point bars have incised (breached) underlying coarse-grained lithofacies, vertical migration can occur. Therefore the lateral extent of a saline plume within a point bar system is influenced by the distribution of the bounding impermeable, fine-grained lithofacies.

By mapping the distribution of coarse-grained lithofacies it was possible to infer the geologic migration pathways through the aquifer because hydraulic conductivity is controlled by the percentage of sand (coarse-grained lithofacies). Therefore, sandstone percentage maps (Plate 06 and Plate 07) were constructed to understand the movement of ground water within the Garber “B1” and “B2” sandstone intervals, because this was the interval where saline impact is present within the Thunderhead Hills subdivision.

To understand hydraulic control on the movement of ground water and saline plume(s), a structure (elevation) map was prepared on the contact between the Garber “B2” sandstone package and top of the Garber “C” package. Mapping of this stratigraphic contact revealed that gross movement of ground water within the study area is generally toward the northwest along a prominent geologic depression (Plate 08).

Movement of ground water, and thus saline plume(s) can also be affected by the presence of utility trenches and the gravel-packed annular space in water wells as they represent preferred migration. The presence of these conditions can further complicate interpretations of how saline plume(s) are distributed in the subsurface.

ELECTRICAL RESISTIVITY IMAGING

ERI has been shown to be a useful tool for delineating the extent of contaminant plumes beneath landfills (Chambers, Kuras, Meldrum, Ogilvy, and Hollands, 2006), the identification of saltwater impact associated with leaky casing strings in wells (Roberts, 2001a), and leaching beneath abandoned brine evaporation pits (Murphy, Kehew, Groenewold, and Beal, 1988).

ERI is a non-invasive investigation method, which measures the electrical properties of shallow subsurface materials. ERI imaging occurs by inducing a direct electrical current into the ground and measuring the resulting potential differences in the subsurface earth materials. The electrical responses that are measured vary in response to changes in lithology, water content, pore-water chemistry and the presence of buried structures. The collected data is then processed using sophisticated inversion techniques to generate ERI profiles, which represent a model of the electrical resistivity properties of the subsurface in units of ohm-meters.

Resistivity values were contoured and plotted using a common color scheme to evaluate all images collected across the study area. Use of a common color scheme provided a consistent way for interpretation and correlation of the results from one survey to another. Conductive (less resistive) areas were illustrated by cooler colors (i.e. purple to blue) and the more resistive (i.e. less-conductive) areas of the subsurface were illustrated by warmer colors (i.e. orange and red). To interpret locations in the subsurface where potential saline impact might be present, a second color scheme was developed to highlight the most conductive anomalies where resistivity values were less than 20 ohm-meters. The remainder of the images was colored in varying shades of gray.

General Observations

The overall quality of the ERI profiles was considered to be good to excellent. Many of the images showed significant lateral and vertical variability in electrical properties. The observed variability implied the presence of possible multiple saline plumes. Some images also indicated the presence of saline waters being sourced from near the surface. These general observations were considered to be consistent with the hydrogeologic conceptual model and the variation in ground water chemical properties.

The following general relationships were used as guidelines for interpreting the ERI survey data:

- Fine-grained lithofacies such as clay and silt were generally more conductive (less resistive), while coarse-grained lithofacies like sandstone were generally less conductive (more resistive).
- Buried man-made structures typically showed up as either very conductive anomalies (metal piping) or very resistive anomalies (concrete, fiberglass).
- Areas suspected to have been impacted by saline intrusion of subsurface soils and/or ground water were typically more conductive that areas where no known or suspected saline impact had occurred.
- Metal pipe produced images having a highly conductive signature. The “noise” pattern created by metal piping was further complicated the interpretation of images where saline discharge from piping might have been present. This problem was resolved by taking into account the following considerations: 1) In most cases, piping was located near the surface, so its conductive signature was located near the top of the image, and 2) saline leaks usually appeared as horizontal departures at depth from a suspected leaky pipe. These considerations were supported by performance of resistivity modeling to specifically evaluate the affect of metal pipe or other objects on the final image.

Survey-Specific Observations

Following is a summary of the interpreted results for each ERI survey recorded in the study area. Individual, two-dimensional subsurface ERI images are presented in Appendix A.

OSU TH.A Survey

The shallow conductive features in the image at the 440 foot, 720 foot, and 960 foot markers correlated to known pipeline crossings identified in the field from records provided by Pedestal Oil Company

Also shown on the survey was the location of a former brine evaporation pit between the 720 foot and 920 foot markers. Location of the brine pit was established using historical aerial photos. The image across the former brine pit indicates that it did not have any significant impact on the subsurface electrical properties beneath it, thus suggesting that brine seepage from the pit had little or no impact on ground water conditions.

The background resistivity of this image was lower than most of the other images. Because the lower background resistivity signature extends through the entire image, it did not appear to be directly related to geologic conditions. A higher resistive layer was indicated at approximately 100 feet below the land surface, but appeared to fade with the color scheme utilized. The overall conductive nature of this image suggested the presence of diffuse saline impact. Verification of this interpretation can only be achieved through performance of invasive evaluation techniques.

OSU TH.B Survey

This dataset was one of two images (see ACOG THH. 05), which were considered to be most representative of background electrical resistivity conditions. Overall resistivities were generally above 75 ohm-meters. Resistivities in some areas were as low as 60 ohm-meters in shallow subsurface portions of the image, which indicated the lithology may consist of fine-grained lithofacies.

The image also displayed some conductive features below a depth of 200 feet almost equidistant between the 320- and 900-foot markers. These anomalies may represent brackish fluid at depth. However, another deeper image would be required to help confirm this interpretation.

OSU TH.C Survey

This dataset was recorded across a number of oilfield pipelines. The pipes are believed to be out of service, as they were reportedly purged of fluid more than 30 years ago. The image shows conductive areas in the subsurface between the pipe interference patterns located at the 290-foot and 660-foot markers. If these anomalies are saline related, the length of time since the pipes were taken out of operation suggests that saline signatures in the subsurface can be very persistent.

The western half of the image appears to be more conductive than the eastern half. The lower resistivity background signature is similar to the conductive values present throughout the entire domain in the OSU TH.A image.

OSU TH.D Survey

Known or suspected pipeline crossings are present in the image at the 140 foot and 430 foot markers.

OSU TH.E Survey

This image has significant utility and oilfiled pipe interference, which affected the overall quality of the dataset. The image is resistive beneath the utility signatures except for a feature located at the 450-foot marker. The physical separation of this feature from the land surface suggests it may not be a pipe interference signature. This feature appears to connect to a conductive anomaly centered at the 300-foot marker at a depth of 200 feet.

OSU TH.F Survey

The placement of the survey was selected in anticipation of acquiring background subsurface resistivity values. However, several features were identified on this image. The characteristics and distributions of the identified anomalies suggest that geologic facies in the area are extremely conductive, or the area was possibly affected by saline fluids. This would not necessarily be unexpected since this site also had oil field activity in the area. A drilling program conducted in this area could possibly resolve this issue.

OSU TH.G Survey

This was the longest survey which collected electrical data in a direction parallel to oilfield piping. This is also the worst quality image in the dataset due to the pipe interference. The line has two conductors that continue to depth; one at the 720 foot marker and a second at the 1560 foot marker. The image suggests that these two conductive areas represent saline impact. However, without confirmation drilling these pipe-associated conductors may represent some odd piping interference instead of saline impact.

OSU TH.H Survey-Common Line

This survey is common with the ACOG THH.03 survey. The TH.H image was developed using the HF data acquisition method. ACOG's THH.03 survey employed standard resistivity data acquisition and processing methods. The images show the presence of an anomaly, which was interpreted to represent potential saline impact at 50 feet below the land surface. The anomalous feature extends to the base of the image to a depth of more than 150 feet.

AGOC THH.01 Survey

This image presents a possible utility interference pattern at the 350-foot marker that extends to the bottom of the image. However, the conductive pattern shows some lateral deviation from the pipeline that may represent saline impact. A second conductive anomaly, centered about the 600-foot marker, is believed to be saline impact. These impacts are discontinuous and were developed at different depths.

ACOG THH.02 Survey

This image has the same general appearance as the THH.01 survey. This image shows shallow pipe noise interference, which exhibits lateral deviation and the development of a conductive feature at a depth of 150 feet between the 300-foot and 630-foot markers.

ACOG THH.03 Survey-Common Line

This image is common with the OSU TH.H survey, but was acquired using standard ERI techniques. Its interpretation is the same as discussed in the OSU TH.H section.

ACOG THH.04A Survey

The conductive feature at the 200-foot marker offsets a domestic well known to be impacted by saline water, and is believed to represent real data, not the edge of a boundary condition. Further to the south, the shallow horizontal low resistive feature at a depth of 30 feet was interpreted as fine-grained lithofacies. This interpretation was supported by information reported on the driller's log of the borehole drilled at 304 Early Dawn Drive (Figure 11), which reported the presence of shale at this depth. The feature is interrupted by suspected pipe interference at the 700-foot marker.

ACOG THH.04B Survey

This image overlaps with the ACOG THH.04A survey. The northern half of this image shows the same profile as the southern half of THH.04A. The shallow, horizontal low-resistive feature seen in THH.04A is present across the entire image; suggesting that it is related to the local geology.

ACOG THH.05 Survey

This image shows mainly background electrical signatures. Based on the THH.03 image, the conductive feature at the south end of the survey is utility interference.

ACOG THH.06 Survey

The conductive features in the image tend to be focused at the bottom boundary. The features may be real data, or a poorly constrained boundary condition in the resistivity model.

Individual ERI survey observations discussed above were based entirely on stand-alone interpretations of the data that was collected and are not considered a comprehensive evaluation. Anomalies interpreted as representing saline impact should be verified by tying the ERI data to known subsurface conditions. This can only be accomplished through performance of a drilling and sampling program.

IDENTIFICATION OF SALINIZATION SOURCE(S)

As already discussed herein, water softener effluent and oilfield formation brine were considered to be the most likely sources of salinization in the study area. To determine which of these two sources was actually the cause of saline impact (particularly in Thunderhead Hills subdivision), a geochemical mixing evaluation was performed by cross plotting the relationships between the ratios of bromide (Br) to chloride (Cl) versus chloride.

The usefulness of Br/Cl plots to differentiate between potential saline sources is well-documented in studies performed by Whittemore (1995), Panno (2006), and Richter and Kreitler (1993). These ions were selected for this exercise because they tend to be conservative, meaning that in the dissolved phase they will migrate at ground water flow velocities, and generally will not react with aquifer whole rock chemistry. During mixing the concentrations of these ion species are affected only by dilution, the effects of which are minimized or eliminated when evaluated using ion ratio plots.

Seven domestic wells were selected in the area affected by the saline plume. Samples of un-impacted ground water and oilfield brine were also collected for analysis of bromide and chloride to define conservative ion end member mixing concentrations. In addition, a solution of Morton Salt pellets used in local water softener brine tanks was prepared for analysis of bromide, sodium and chloride.

Brine End Member Selection

Chemical analyses representative of oilfield brines were obtained for various geologic formations (Table 2) from wells in sections 28, 29, 31 and 33 of T14N-R2W. A Schoeller diagram (Figure 12) was prepared to aid in geochemical characterization of these brines. While some separation was noted between the brine from Section 33-T14N-R2W and the other brines, generally, the ratio plots indicate that there is minimal difference in the geochemical composition of the brines. Because the formation brines were so similar geochemically, brine chemical data of produced water from the Pedestal Oil Company No. 1 Darwin well was considered to be representative of all oilfield brines in the immediate vicinity of the study area, and was used to represent the oilfield brine end member in the mixing equation.

To ensure that a representative sample of un-impacted Garber ground water was used to evaluate mixing relationships, published geochemical data of ground water samples collected by the USGS from the NOTS No. 3 Test Well located in Section 23-T14N-R02W, Oklahoma County were used (Schlottmann and Funkhouser, 1991). This test well was located approximately two and one-half miles east of the Thunderhead

Hills Addition, and had a reported bromide concentration of 0.15 mg/L. To aid in verifying this sample was representative of Garber ground water conditions in the study area, a comparison of ion concentration values reported in the 1999 OCC geochemical data was made. The two data sets were found to be very similar.

Published data was used as the basis for characterizing the Br/Cl ratio of water softner salt pellets; specifically, data from the study by Panno, et al, (2005). In that study, a Br/Cl ratio of 0.000176 was reported for a solution prepared using Morton Salt pellets. In the same study, a Br/Cl ratio of 0.00029 for Culligan water softener salt was reported. Studies by Davis and Whittemore (1998) have reported septic system Br/Cl ratios that were comparable to the Panno, et al (2005) study.

Ion concentrations for all water samples used for evaluating geochemical mixing relationships are presented in Table 5.

Mixing Curve Analyses

Using the data in Table 5, conservative mixing curves were plotted for the following end member pairs:

- Garber background water and water-oilfield brine;
- Garber background water and water softener regeneration brine; and,
- Garber background water and sea water.

The following mixing equation, adapted from Whittemore (1995) was used to generate mixing curves for each end member pair:

$$\mathbf{C_m = X*C_f + (1-X)*C_s}$$

where: C_m = Constituent concentration (ratio) in mixing water,

C_f = Constituent concentration (ratio) in background water,

C_s = Constituent concentration (ratio) in brine water,

X = Volume fraction of background water in the mixture, and

1-X = Volume fraction of brine in the mixture.

The mixing curves associated with each of the end member pairs are shown in Figure 13.

The Br/Cl ratios of impacted ground water from six of the domestic wells in the Thunderhead Hills subdivision were plotted to see where they fell in relation to the end member mixing curves. All of these samples plotted along and near the mixing curve for water softener brine. This result clearly indicates that saline impact to the private domestic water wells in the Thunderhead Hills Addition was associated with water softener brine and not oilfield brine.

SALINE PLUME CHARACTERIZATION

The generalized boundary of anthropogenic-sourced saline waters in the Thunderhead Hills Addition is delimited by water type distributions (Figure 10) and the associated “hardness halo” (Figure 06). The definition of the plume(s) inside this boun-dary is based on the compilation of multiple lines of evidence through:

- Recognition of saline water expansion based on historical water chemical data. The data aided in identifying where, and when, saline problems first appeared and in documenting plume migration suggested by the relative increase in saline indicator concentrations in the same well or between nearby wells over time.
- The use of kriging, a geostatistical gridding method, to recognize data trends and regions of steep chemical gradients that were interpreted as plume edges possibly caused by a geologic lithofacies changes.
- Recognition of ERI image conductive zones near well control with known saline impact.
- Recognition of the lateral departure of low resistive anomalies from known pipeline noise interference which could represent saline water zones.
- Recognition of ERI conductive zone alignments and limits, which may provide insight to saline plume migratory pathways.

Interpretation of the ERI images, in conjunction with the OCC 1999 water chemical data, revealed a complex pattern of multiple plumes not previously indicated when only the water data analyses were taken into consideration. Since the salinization source is water softener brine and 60% of the residents own water softener units, the likelihood of multiple plumes could be expected.

The plume patterns are shown in Figure 14. The limit of plumes “A” and “B” corresponds to a chloride concentration of 500 mg/L, while the limit of plumes “C” and “D” was established at 250 mg/L. This approach of illustrating the plume differentiation was chosen because mapping of the electrical signatures, interpreted as saline water, resulted in the overlap of dissimilar plumes in areas where they were developed at different depths.

Plume A

In 1987, chloride levels of 1700 mg/L were measured in the domestic well at 2901 Timothy Way along the interpreted western edge of the plume. This was the first indication verifying the existence of the plume. Of all the plumes, Plume “A” appears to be the one most extensively developed. Within Thunderhead Hills, the plume path extends from the northern boundary southwestward approximately 780 feet to the intersection of Sherrywood Lane and North Coltrane. In addition, the highest chloride levels recorded in the Thunderhead Hills Addition were associated with this plume. The delineation of Plume “A” was substantiated based on the following evidence:

- The isolated, low resistivity anomaly in the TH.H image, developing at a depth of 50 feet between the 180-foot and 550-foot markers, is believed to be a northern expression of Plume “A”, because the anomaly directly offsets an area of relatively high saline impact identified by the water chemical data.

- The eastern limit of the conductive layer in the TH.H image corresponds with a well-defined, steep chloride concentration gradient portrayed on contour maps of the 1991 and 1999 water data. The existing well control permits the extension the concentration gradient to wells located south of Timothy Way. The gradient was interpreted as representing the eastern limit of Plume “A”.
- The anomaly in the TH.H image and another centered at the 600-foot marker in the THH.01 image show a perceptible north-south alignment. The eastern edge of both anomalies corresponds with the steep chloride concentration gradient, both have similar lateral development, and both are vertically positioned at an approximate depth of 50 feet offsetting high saline-impacted wells. Based on these findings both anomalies are believed to be manifestations of the same plume.
- The water well driller’s log at 3001 Timothy Way shows the anomaly centered at the 600-foot marker (Figure 15) is likely associated with a shale-enclosed sandstone interval. This provides further confidence to the interpretation that this feature is saline-related.
- The extension of plume “A” southward and its separation from plume “B” to its east is based on the THH.02 survey and trends observed in the historical water chemical data. The anomaly at the western end of the THH.02 survey (830 foot marker) would typically be assessed as being generated by edge effects. However, because it directly offsets a domestic well which had chloride levels of 1237 mg/L in 1999, the anomaly is believed to represent real data. The same well, which is located at 2901 Sherrywood Lane, exhibited chloride levels of 364 mg/L eight years earlier. The chemical data from other wells located east and south of this well were considered to be representative of background aquifer conditions in 1991 and 1994 based on sampling results. The water chemical data confirms that in 1991 the leading edge of Plume “B” had not yet reached this area of Thunderhead Hills. The appearance of Plume “B” in this area was established by the 1997 water data set.

The source area for plume “A” appears to be north of the Thunderhead Hills Addition. At the time of conducting this project, all of the original domestic wells located within the limits of this plume had been plugged and replaced with deeper wells producing water from the Wellington Formation. The single exception was the landowner at 2901 Sherrywood Lane who opted to connect to the City of Edmond’s water service. As a result, no samples for bromide analysis could be collected at these residences to aid in corroborating a salinization source.

An examination of the *Potential Sources of Salinization* map (Figure 3, Plate 02) and water samples collected from a well in the southeast corner of the Faith Bible Church property point to two source possibilities; both located on the church property at 600 North Coltrane. One possibility is a yet to be identified septic system whose existence is based on the water well Br/Cl ratio being similar to expected ratios when fresh water mixes with water softener brine. In addition, nitrate levels, which are associated with septic tank systems, were measured at 39 mg/L in this well. The other possible source is leakage from an abandoned saltwater injection line. According to information provided by Pedestal Oil Company, this line crossed the church property near the south side of the church sanctuary. Further field work will be necessary to determine if either of these possibilities are contributing to plume “A”.

Plume B

Plume “B” manifests itself near apparent pipe interference indicated by ERI surveys THH.01 and THH.02. The positions of the interference signature in these images match well with a known natural gas pipeline. Both conductive anomalies show lateral deviations from the pipe signature at a depth of 50 feet that were interpreted as saline water impact. Plume “B” is believed to originate in the Thunderhead Hills Addition because a matching con-ductive anomaly is not identified in the western end of the TH.H image.

Of significance, pipe interference was not observed in the THH.05 image, located north of THH.01, even though the survey paralleled the natural gas pipeline. Since non-metallic materials were used in the pipeline construction, the absence of interference would be the expected electrical response. Therefore, the pipe interference shown in THH.01 and THH.02 images is believed to reflect saline migration along the piping trench connecting the north and south portions of plume “B” (Figure 14). The connection is fur-ther supported by the similar Br/Cl ratio shifts noted by the geochemical data for the domestic wells at 3009 Timothy Way and 301 Early Dawn Drive; both of which are in close proximity to the piping run.

The conductive zone at a depth of 150 feet in the THH.02 image is interpreted to be the consequence of downward migration of saline water via the annular space in the irrigation well located southeast of the Pedestal Oil Company # 1 Darwin well. From this well, the continued migration of Plume “B” to the southwest is believed to be represented by this conductive zone between the 300-foot and the 660-foot markers in the THH.02 image.

Plumes C and D

When compared to the previously discussed plumes, Plumes “C’ and “D” show limited development and exhibit lower maximum dissolved chloride concentrations. While these plumes may be connected, their separation was based on the Ca/Na and Na/Cl ratio maps (Figures 06, 07). Possible origination points were the septic tank systems located at 305 Early Dawn Drive and 408 Early Dawn Drive. However, it should be noted that the Plume “D” source could be located north of Thunderhead Hills.

Regional Plume Distribution

Outside Thunderhead Hills, ERI surveys were placed to obtain data that characterized background subsurface conditions and delineate the extent and cause of ground water impact by oilfield activities. ERI surveys TH.E and TH.G were oriented perpendicular and parallel, respectively, to abandoned oilfield pipeline runs located north and east of Thunderhead Hills. Surveys TH.A and TH.C evaluated the subsurface conditions beneath an evaporation pit observed on historical aerial photographs, and surveys TH.B and TH.F were placed to characterize background subsurface electrical signatures. The OSU survey TH.H was common with the ACOG survey THH.03 for use as a comparison between standard ERI methods employed by ACOG and the OSU proprietary HF method.

Review of the surveys (Figure 16) located outside the Thunderhead Hills Addition lead to the following observations:

- A low resistivity anomaly, which would indicate leakage, was not present beneath the evaporation pit on surveys TH.A or TH.C.
- Pipe associated conductive zones exhibiting lateral deviation were observed on surveys TH.C and TH.G. The electrical signatures may be showing vertical saline migration subsequent to pipeline abandonment; however, confirmation drilling will be required to determine if these images represent saline impact or pipe interference. If drilling confirms the images are related to a saline release, additional surveys will be necessary to delineate the limits of degradation.
- The low resistivity anomaly on survey TH.E at a depth of 200 feet may represent either leakage from an abandoned injection line, effluent discharge from a nearby septic system or just the extension of plume “A” to the north.
- Anomalies were present at depth on survey TH.F at the 420 foot and 970 foot markers. These interpreted saline zones may be in hydraulic connection with Spring Creek. However, surface water sampling conducted by ACOG near Interstate I-35, upstream from where Spring Creek discharges into Arcadia Lake, shows no increased chloride levels.

While additional field work will be required for confirmation, the anomalies observed outside the Thunderhead Hills Addition are believed to be related to oilfield activities.

SUMMARY AND CONCLUSIONS

The project assessed the saline impact in the Thunderhead Hills Addition and surrounding area. The subdivision was built on the footprint of oilfield production that was discovered in 1943, and since the addition's development in 1973, the residents have used domestic wells and septic tank systems to provide water and waste-water services. The investigative approach applied ERI, subsurface mapping, and evaluation of geochemical mixing relationships to delineate the distribution and identify the source(s) of salinization. The project findings, presented herein, were based on the following lines of evidence:

- Saline plume development is restricted to the upper Garber Formation. Geophysical log signatures and the mapping of depositional patterns show that this stratigraphic sequence exhibits fluvial depositional characteristics that could influence the path of plume migration. Further confidence in this interpretation was gained when the evaluation of the ERI surveys revealed a complex pattern of multiple plumes, which was not previously indicated by the water quality data.
- A review of historical land uses and site specific conditions ruled out the likelihood of agricultural practices, road deicing applications or mixing with deeper formation brines as salt sources causing the observed saline impact.
- Geochemical modeling shows that the accumulated effects of continued water softener cycling are the principal source of salt pollution within the Thunderhead Hills Addition. Outside Thunderhead Hills, electrical signatures, believed to represent saline impact, are associated exclusively with oilfield activity. Therefore, oilfield brine is believed to be the salt source for these features.
- Aquifer hydraulic control, based on the Base/Garber "B" Unit structure map, shows the direction of plume migration is toward the west-southwest away from Spring Creek. This implies that the Thunderhead Hills Addition saline plume will not discharge to Spring Creek. At the time of conducting this assessment, the ongoing periodic collection of surface water samples just west of Spring Creek's confluence with Arcadia Lake has never shown any indications of chloride impact.
- Based on the depth, location and inferred migration direction of the saline plumes, the potential for saline water to "daylight" and enter into tributaries of Spring Creek and ultimately end up in Arcadia Lake is considered to be a remote possibility at best.
- The Thunderhead Hills Addition saline plume(s) should not hinder any future expansion planned for the City of Edmond water well field south of the project area, if the municipal wells are completed in the underlying Wellington or deeper geologic formations.
- Several low resistivity anomalies were identified on ERI surveys placed outside the residential development. However, due to significant pipe interference and sparse ERI coverage, it was not possible to correlate the anomalies with any degree of confidence. Additional ERI surveys backed by subsurface drilling will be required to confirm these anomalies as saline water related pollution as well as to identify the salt source.

RECOMMENDATIONS

Based on the findings of this study the following recommendations are presented for consideration:

- The drilling restriction outlined under Appendix H, Title 785, Chapter 45 of the Oklahoma's Water Quality Standards, should remain in force. This restriction requires that all new domestic wells be cased and cemented through the zone of salinization.
- Because of the ubiquitous water "hardness" problem, future residential development considering household septic systems as their sole wastewater service should assure septic systems are properly constructed and that lots are sized appropriately to minimize the potential problems caused by water softener cycling discharge.
- Point-of-use water treatments, such as reverse osmosis, appear to be the most economical approach for addressing the chloride pollution since the septic systems will be a continuing supply of brine for the plumes. This approach, however, is not proactive in mitigating the saline plume and leaves the financial burden with the homeowner.
- The shallow domestic wells impacted by brine can be plugged and replaced with deeper wells producing water from the underlying Wellington Formation. This approach, while assuring a supply of potable water for consumption and irrigation, does not address the issue of plume remediation.
- Another approach, considered a long-term, permanent solution, would require that the City of Edmond provide water and wastewater services to the residents in the Thunderhead Hills Addition. This approach would eliminate the brine source and allow the plume to attenuate over time by natural processes. A more aggressive remediation approach would involve the installation of recovery wells for remediation of saline water.
- The empirical relationships developed by this project have not undergone a comprehensive evaluation. Field drilling should be conducted in such a way as the ERI survey interpretations can be tied to known subsurface conditions.
- The origination point and saline source for Plume "A" have yet to be identified. Additional field work will be necessary to determine if the point of origination of the, determine if the plume is still migrating, or if it has achieved steady state conditions or is attenuating.
- While the saline source within the Thunderhead Hills Addition has been identified through evaluation of geochemical mixing relationships, additional field work will be required to identify and confirm plume origination locations.
- Further investigation is needed to determine if the low resistivity anomalies observed on the ERI surveys outside the Thunderhead Hills Addition, are actually saline-related features.

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