Integrated Water Resources Engineering
Innovative Solutions for Water and Land

Lost Creek Underground Storage Pilot – 2018 Groundwater Investigation Report

Prepared for:

The City of Aurora
The Town of Castle Rock
(with funding support from Colorado Department of Natural Resources PO # POGG1 PDAA 201700001081)

November, 2018

Project No. 1412AUW02

The technical material in this report was prepared by or under the supervision and direction of the undersigned Professional Geologist.

Dave Colvin, PG, PMP

The following members of the Leonard Rice Engineers, Inc. staff contributed to the preparation of this report.

Principal in Charge	Dave Colvin, PG, PMP
Project Hydrogeologist	Joel Barber, PE
Senior Project Hydrogeologist	Jacob Bauer, PG
Senior Hydrogeologist	Lauren Handley, PG
Senior Advisor	Gary Gin, PG
Senior Advisor	Cortney Brand, PG, PMP
GIS Technician	James Tobler

Table of Contents

List of Tables

List of Figures

List of Appendices

1 EXECUTIVE SUMMARY

THIS STUDY BUILDS ON PREVIOUS RECHARGE INVESTIGATIONS AND IS PRESENTED AS CURRENT BEST PRACTICES FOR FEASIBILITY EVALUATION OF UNDERGROUND WATER STORAGE IN THE ALLUVIAL AQUIFERS OF THE SOUTH PLATTE RIVER AND ITS TRIBUTARIES.

Additional water storage is widely recognized as an important need for successful water resources management in Colorado's South Platte River Basin. There are many storage methods and locations to be considered. This report focuses on underground water storage (also called managed aquifer recharge [MAR], or aquifer storage and recovery [ASR]), in the unconsolidated alluvial aquifers of the South Platte River and its tributaries. More specifically, this study has evaluated field methods for assessing the feasibility of underground water storage in localized areas. Several regional underground water storage studies have been previously completed using desktop methods.

This study was a collaborative project between Aurora Water and Castle Rock Water. Additional funding was provided by the Colorado Water Conservation Board. Leonard Rice Engineers, Inc. has worked with Aurora Water and Castle Rock Water to plan, implement, and document this project. The Lost Creek Ground Water Management District has participated as a stakeholder and has provided valuable input throughout the project.

Previous statewide and regional studies have ranked the Lost Creek Basin as a preferable location for underground storage due to deep bedrock, thick unsaturated alluvial deposits, and the unique water administration from being primarily within a Designated Basin[1]. For these reasons, the Lost Creek Basin was chosen for this study. During the initial project planning, field investigation locations were identified where: 1) existing data indicated recharge was feasible; 2) unsaturated alluvial deposits are relatively thick; and, 3) property owners would allow field investigation on their property. Three locations were selected for field investigation but are not accurately located due to property owners' requests to remain anonymous.

We identified field investigation methods that were cost effective and have been used previously for alluvial groundwater investigations. Field investigation methods included geophysical surveys, surface infiltration tests, exploratory borehole drilling, and downhole infiltration testing. These methods were tested and compared to evaluate which are most appropriate for assessing local aquifer capacity for water infiltration. To some extent, the results from this investigation can be extrapolated for regional evaluation of water infiltration, storage, and recovery.

Table 1-1 below presents the various methods used and an assessment of their advantages and disadvantages.

[1] Designated Basins are areas in the Eastern Plains of Colorado where surface water is scarce and the primary supply is groundwater. Designated Basins are administered by the Colorado Groundwater Commission and local Groundwater Management Districts, outside of Colorado's prior appropriation water rights system.

Table 1-1 Field Investigation Methods Used During the Project

Field Method	Advantages	Disadvantages
Sonic Exploratory Borehole Drilling	• Provides accurate and detailed continuous lithologic logs/samples • Provides access for infiltration testing at depth • Provides the highest quality lithology data that can be used to calibrate geophysical data	• Relatively expensive • Drilling disturbs the land surface and may interfere with other land uses • Data limited to one location and requires multiple boreholes to investigate spatial heterogeneity
Time Domain Electromagnetics (TDEM) Geophysical Surveys	• Interpreted results provide information about subsurface material grain size and layering • Equipment can be configured for different resolution at different depths	• Does not provide important cementation or consolidation information • As configured for this project, TDEM did not provide adequate resolution to characterize the vertical heterogeneity observed in boring lithology • 3-D interpretations were not confident as the results did not correlate with observed lithology
Frequency Domain Electromagnetic (FDEM) Geophysical Surveys	• Results can be interpreted to represent bulk grain size data for upper 30 feet of the subsurface • Interpretations were confident because they closely correlated to borehole lithology logs	• Does not provide important cementation or consolidation information • Provides a bulk measurement of the top part of the aquifer and therefore cannot provide important layering information

Field Method	Advantages	Disadvantages
Electrical Resistivity Tomography (ERT) Geophysical Surveys	• Interpreted results can relate electrical resistivity to subsurface material grain size	• Did not provide a fine enough resolution to characterize the vertical heterogeneity of the alluvial deposits
Multi-channel Analysis of Surface Waves (MASW) Geophysical Surveys	• Shear wave velocity can be interpreted to indicate density, and extrapolated to represent the degree of cementation and the depth to consolidated bedrock	• Does not provide information about subsurface material grain size
Double-Ring Infiltrometer Surface Infiltration Testing	• Provides a direct measurement of infiltration rates for surficial materials	• Data limited to one location and requires multiple tests to investigate spatial heterogeneity • Tests only the near-surface soils and the results are not influenced by deeper soil horizons
Constant-Head and Falling-Head Downhole Infiltration Testing	• Provides a direct measurement of infiltration rates at depth • Provides observations of relatively low and high permeability zones	• Results are uncertain and interpreted saturated hydraulic conductivity values can vary significantly from true values • Data limited to one location and requires multiple tests to investigate spatial heterogeneity

1.1 FIELD METHOD CONCLUSIONS

We co-located field method testing sites so that results from different methods could be compared. The following is a summary of findings regarding the various field investigation methods tested:

- Surface geophysical surveys are a reliable means to characterize large areas of the subsurface, but should be locally calibrated and verified by exploratory boreholes. The geophysical results can provide valuable information for siting exploratory boreholes.

- The exploratory borehole lithology observations were the most detailed and accurate characterizations of subsurface materials, and were used as the baseline data to compare other results. The sonic drilling method provided high quality, continuous soil core samples necessary for characterizing the high degree of vertical heterogeneity of the lithology.

- FDEM interpreted results closely matched the exploratory borehole observed net sand thickness in the top 30 feet of the subsurface. FDEM results provide a reliable, relative characterization of the bulk grain size in the top 30 feet of unsaturated alluvial deposits.

- TDEM results did not have the resolution necessary to provide useful subsurface characterization for this project. The method could be adapted to have multiple passes with different equipment configurations (coil sizes). With proper configuration, TDEM may provide a reliable, relative characterization of the grain size and layering in unsaturated alluvial deposits.

- MASW interpreted results closely matched the borehole aquifer cementation and bedrock depth observations. MASW results provided a relative measure of cementation and bedrock depth in unsaturated alluvial deposits.

- ERT results were unreliable and are not recommended for future investigations.

- The interpretations of saturated hydraulic conductivity from the downhole infiltration tests are known to be uncertain. Therefore, the interpreted values are meant to give a relative, qualitative permeability estimate and not a precise value suitable for engineering design purposes.

- Surface double-ring infiltrometer testing provided a direct measurement of infiltration rates into surficial soils.

- The methods presented here are not exhaustive and additional field investigation technologies and methods should continue to be considered.

1.2 LOST CREEK BASIN HYDROGEOLOGIC CHARACTERIZATION CONCLUSIONS

We have made the following conclusions regarding the hydrogeologic characteristics of Lost Creek Basin as they relate to underground water storage planning:

- The alluvial deposits are vertically variable with frequent very thin to thick alternating beds of sand, clay, clayey sand, and sandy clay, with some gravelly areas. Intermediate clay beds were observed in all three test holes. These intermediate clay beds have the potential to present challenges for groundwater recharge. The lateral continuity of these beds and their potential effect on infiltration rates is important and should be further characterized.

- Near surface (shallower than 10 feet below ground surface) fine grained material may inhibit infiltration and should be specifically investigated, even in areas where the deeper deposits are permeable.

- Significant cementation of the alluvial aquifer vadose zone material was observed in two of three test holes.

- The degree of cementation influences permeability and porosity of the alluvial deposits and is a key planning consideration for underground storage at this location.

- Older alluvial deposits generally form topographic highs (terraces), are weakly to well cemented, and display a low to moderate permeability that is less conducive to infiltration. In these older alluvial deposits, the permeability of the subsurface material is not correlated to the gradation and is controlled by the cementation.

- Younger alluvium exists in topographically low spots, was generally loose, poorly cemented, and displayed moderate to high permeability; which is more conducive to infiltration.

- These conclusions are specific to the areas of the Lost Creek Basin that were investigated but are likely applicable to underground storage planning in other alluvial aquifers of the South Platte River and its tributaries.

1.3 RECOMMENDATIONS

Planning of underground storage will benefit from a phased feasibility investigation approach starting with regional or basin-scale investigations followed by localized field investigation. We recommend the following for future feasibility studies of underground storage in the alluvial aquifers of the South Platte River and its tributaries.

1.3.1 Basin Scale or Regional Investigations

- The cementation of the older alluvial deposits is a critical underground storage consideration and is not identified in regional studies, such as the 2011 Lost Creek Basin Aquifer Recharge and Storage Study (CGS, 2011). The reduction in pore space and permeability due to cementation may result in a lower amount of available storage than previously characterized. A desktop study should be conducted to re-evaluate available storage and permeability in the aquifer assuming that the older alluvial deposits are moderately to well cemented.

- Field mapping should be used to refine the available surficial geology and soil maps with a focus on mapping the younger and older alluvial deposits.

- Two-dimensional seismic profiles may help to characterize the distribution of cemented aquifer materials over larger areas.

- Basin/regional scale investigations and underground storage planning may also benefit from three-dimensional geologic modeling and groundwater flow modeling.

- If the conclusions of this study continue to hold true with additional investigation, local field investigations for recharge potential should be focused in the younger Piney Creek and Post Piney Creek alluvial deposits.

1.3.2 Local or Parcel Scale Investigations:

- The potential effect of shallow clay layers in the younger alluvium and the lateral continuity of these clay layers should be further investigated.

- Future investigations should include longer term infiltration testing using test pits or pilot infiltration basins to better characterize realistic infiltration rates. These tests should include observations of the wetting front and changes in groundwater levels throughout the test.

- Future parcel scale investigations should utilize FDEM geophysical surveys to optimize the location of infiltration basins and to target the relatively coarse materials in the top 30 feet of the alluvium.

- Future investigation utilizing the TDEM geophysical method should modify the equipment configuration to investigate the shallower materials in greater resolution.

- Future site investigations should include characterization of alluvium cementation. We recommend the use of seismic geophysical methods (such as MASW) in combination with test holes to characterize the degree of cementation in the alluvium.

- Future local-scale investigations should consider additional methods for investigating the existence and impact of vertical layering and lateral continuity of layers.

- Three dimensional geologic modeling and vadose zone/groundwater modeling should be conducted to evaluate the recharge and associated recovery of recharged water.

The results of this study continue to show that there is good potential for underground storage of water in the alluvial aquifers of the South Platte River and its tributaries. Using the recommended investigation methods presented herein will increase the success of underground storage projects.

2 INTRODUCTION

The City of Aurora (Aurora), in partnership with the Town of Castle Rock (Castle Rock), contracted Leonard Rice Engineers, Inc. (LRE) to evaluate field investigation methods related to assessing underground water storage potential. The objectives of the field investigations are to refine previous desktop hydrogeological characterization and to evaluate the effectiveness of subsurface investigation methods. The Lost Creek Ground Water Management District (LCGWMD) provided input on the project as an interested stakeholder.

Water storage has been identified as a critical need for the State of Colorado (State) to overcome the projected gap between future water supplies and demands. The 2016 State Water Plan identified 400,000 acre feet of water storage needs by 2050. The South Platte Basin has the majority of Colorado's water demand with most of the population and a significant portion of its agriculture. Identifying storage opportunities in the South Platte Basin is a crucial component of closing the State's future water supply gap. The South Platte Basin Implementation Plan (SPBIP, http://southplattebasin.com) calls for storage projects, including underground water storage or aquifer storage and recovery (ASR).

Following on the prior statewide and basin-scale planning efforts, the 2016 Colorado Legislature appropriated State funding for underground storage pilot projects in the Colorado Water Conservation Board (CWCB) Projects Bill (SB16-174). The legislative language specific to underground water storage is quoted below.

> *SECTION 8. Underground storage pilot project - appropriation. (1) For the 2016-17 state fiscal year, $200,000 is appropriated to the department of natural resources for use by the Colorado Water Conservation Board. This appropriation is from the Colorado Water Conservation Board construction fund created in section 37-60-121, C.R.S. To implement this section, the Colorado Water Conservation Board may use this appropriation to conduct an underground storage pilot project to further evaluate the suitability of various aquifers to store water, availability of water to be stored, and a conceptual framework to initiate an underground storage project.*
>
> *(2) The money appropriated in subsection (1) of this section remains available for the designated purposes until the project is completed.*

The CWCB awarded SB16-174 grant funding to this project under Colorado Department of Natural Resources PO# POGG1 PDAA 201700001081.

LRE conducted site investigations at three locations in the Lost Creek Basin (Site A, Site B, and Site C). Time Domain Electromagnetics (TDEM) and Frequency Domain Electromagnetics (FDEM) investigations were conducted at all three locations. A surface electrical resistivity tomography (ERT) survey was conducted at two of the locations (Site A and Site C). One test hole was completed at Site A and two test holes were completed at Site B. Exploratory test holes were drilled with a sonic drill rig. Downhole permeability testing was conducted during test hole drilling and sampling. Multichannel Analysis of Surface Waves (MASW) seismic reflection surveys were conducted at each of the test hole locations. Finally, four surface infiltration tests were conducted at Site A and three surface infiltration tests were conducted at Site B (**Figure 1**).

3 LOST CREEK DESIGNATED BASIN GEOLOGY AND HYDROLOGY

A geologic map of the basin and summary of the geologic units of the Lost Creek Basin are presented in **Appendix A**. This is the best available geologic map of the area, and to our knowledge, the Lost Creek Basin has not been mapped in greater detail.

The basin is composed of the following geologic deposits, listed from youngest to oldest (Colorado Geologic Survey [CGS], 2011):

- Holocene and Pleistocene age eolian sands and loess up to 100 feet thick. The deposits form long, narrow, dunes trending northeast – southwest.
- Holocene age Piney Creek and Post-Piney Creek Alluvium is located along the current low lying drainages and dry river channels. Throughout this report the Piney Creek and Post-Piney Creek Alluvium is often referred to as "younger alluvium". The younger alluvium is composed of clay, silt, sand, gravel, and cobbles, and has less cementation.
- Pleistocene age alluvial deposits are typically located above the existing drainage and active river channels in the basin. Throughout this report these Pleistocene alluvial deposits are referred to as "older alluvium". The older alluvial deposits are composed of clay, silt, sand, and gravel, are more cemented, and are often roughly to well stratified with distinct layering.
- The Quaternary units are underlain by Cretaceous and Tertiary sandstone, shale, and claystone of the Denver Basin (Denver, Arapahoe, Laramie, and Fox Hills units).

The Lost Creek Basin is an ephemeral tributary of the South Platte River. The main Lost Creek channel is fed from the south by its ephemeral tributaries Long Draw and Sand Creek. The streams do not maintain flow, are not fed directly by groundwater and only flow in response to precipitation events. The total drainage area is approximately 433 mi^2, approximately 43 miles long and 14 miles wide (CGS, 2011).

A basin-wide potentiometric surface was interpreted in CGS, 2011, based on recorded well water levels. In general, water levels are deeper in the southern and central parts of the basin (50 feet to greater than 100 feet below ground surface) and are shallower to the north, closer to the South Platte River (as high as 10 feet below ground surface). The slope of the water table results in the maximum unsaturated alluvium thickness in the southern and central portion of the aquifer, with less unsaturated alluvium in the northern part of the basin (CGS, 2011).

4 PREVIOUS STUDIES

The State has funded several previous studies that evaluated the feasibility of underground water storage at the State and basin scale (**Table 4-1**).

Table 4-1 - Previous Underground Water Storage Publications

Title	Publisher	Author	Year
Artificial Recharge of Ground Water in Colorado - A Statewide Assessment	Colorado Geological Survey	Ralf Topper, Peter E. Barkmann, David A. Bird, and Matthew A. Sares	2004
SB06-193 Underground Water Storage Study	Colorado Water Conservation Board	CDM	2007
Lost Creek Basin Aquifer Recharge and Storage Study	Lost Creek Ground Water Management District and Colorado Geological Survey	Nicholas Watterson and Ralf Topper	2011
South Platte Storage Study	South Platte Basin Roundtable	Stantec and Leonard Rice Engineers	2017

5 SITE INVESTIGATIONS

LRE conducted site investigations at three locations within the southern portion of the Lost Creek Basin. During the initial project planning, field investigation locations were identified where: 1) existing data indicated recharge was feasible; 2) unsaturated alluvial deposits are relatively thick; and, 3) property owners would allow field investigation on their property. Three locations were selected for field investigations. Sites A and B were on private property and the locations of which are not presented in this report at the property owner's requests. Site C is located along a public right of way and the location is included in this report.

The field investigation was conducted in a phased manner to utilize the data collected in each phase to inform the investigations of the following phases. Geophysical investigations were initially conducted at all three sites. Based on the preliminary results of the geophysical investigations, one test hole location was selected at Site A and two test holes locations were selected at Site B. Additionally, four surface infiltration test locations were selected at Site A and three surface infiltration test locations were selected at Site B. **Figure 1** and **Figure 2** shows the field investigation locations for each site.

5.1 GEOPHYSICAL INVESTIGATIONS

Olson Engineering (Olson) was subcontracted by LRE to perform all geophysical surveys associated with the project. The types of geophysical surveys conducted measure variations in electrical resistivity (or its reciprocal, conductivity) and seismic wave travel times. The collected data are then interpreted, and correlated with other lines of evidence, to assess subsurface properties such as changes in lithology, cementation, moisture content, and the relative amount of coarse or fine grained material. The objectives of the geophysical investigation were to:

- Evaluate the vertical layering in the Lost Creek Basin,
- Investigate potential for laterally continuous clay beds,
- Characterize the bedrock contact, and
- Aid in siting test hole and surface infiltration locations.

The following descriptions of the geophysical techniques used were provided to LRE by Olson.

5.1.1 Time Domain Electromagnetics (TDEM) [Provided by Olson]

Olson used the Dynamic NanoTEM (DNT) system by Zonge International, Inc. to acquire the time domain electromagnetic data. The DNT allows for continuous acquisition of TDEM data and incorporates positional data via an integrated GPS. The TDEM survey technique involves transmitting a 50% duty cycle, time domain, square-wave signal into an ungrounded loop of wire. This square wave signal alternates between positive, zero, negative, and zero voltages. The measurements are made when the transmitter is off, i.e., when the transmitter voltage is zero. During these times, decaying magnetic fields from subsurface conductors can be measured. The decaying voltages can be mathematically modeled, providing a vertical sounding of resistivity beneath the receiver loop.

The DNT transmitter is capable of turning off in less than 2 microseconds, and the receiver's first measurement point (corresponding to the shallowest data) is at 4.5 microseconds after turn-off. This fast turn-off and high sample rate allow for good vertical resolution in the near-surface. The turn-off time and sample rate can be adjusted according to the size of the transmitter loop, where the size of the loop is designed specifically for the depth of investigation and the resolution required.

Depth of investigation is dependent on the size of the wire loops while lateral resolution is controlled by the down line station separation. In the field, two square loops of wire were used for the transmitter and receiver loops. This is called a coincident loop as the transmitter and receiver wire are coincident with each other. The signal is transmitted into the transmitter loop and received by the receiver loop. The transmitter loop was 40 x 40 feet in Site A and Site B, and 15 x 65 feet in Site C. Data were collected over Site A and Site B at line spacings of 196 to 295 feet and 330 to 560 feet, respectively, with both north-south and east-west traverses, and over Site C a single 2,590 feet line was collected in the east-west direction.

The advantage of the DNT is the ability to continuously acquire TDEM data while moving the transmitter-receiver loop along the survey profile. Data acquisition with the DNT allows for dense down-line station spacing. Data were continuously recorded at 32 Hz and then stacked during data processing, resulting in average down-line station spacing of less than 3 feet. The receiver operator monitored data quality and positional data in real time to verify system performance. The DNT system has an integrated Global Positioning System (GPS) capable of decimeter level accuracy for sensor positioning. GPS data were recorded at a rate of one reading every second and were written directly into the raw data file.

The results of the TDEM survey at the three survey locations are presented on **Figure 3** through **Figure 8**.

5.1.2 Frequency Domain Electromagnetics (FDEM) [Provided by Olson]

An FDEM instrument consists of a transmitter coil which generates a primary electromagnetic field at a specified frequency separated by some distance from a receiver coil which measures the response (secondary) electromagnetic field generated due to the interaction of the soils to the primary field. This allows for simultaneous measurements of both the in-phase and the quadrature components of the secondary magnetic field generated in the receiver coil. The quadrature component is most sensitive to electrical conductivity, generally due to changes in lithology, moisture, and/or fines (clay) content, whereas the in-phase component is most sensitive to magnetic susceptibility, generally due to the presence of metallic features in the subsurface, either ferrous or non-ferrous.

The FDEM data were acquired using a DUALEM-4 terrain conductivity meter mounted to a cart and were recorded at a rate of 1 Hz, using a primary field of 9.8 kHz with an antenna spacing of 12 feet. GPS measurements were embedded into the data stream at a rate of 1 Hz to allow for precise data positioning. Data were collected over Site A and B at line spacing of 260 to 390 feet, with both north-south and east-west traverses. Data were collected over Site C in a single 2,790 feet line spacing in the east-west direction.

The DUALEM is generally sensitive to a depth range of approximately 10 to 20 feet. This sensitivity range, or the "effective depth", is a response to the orientation and spacing of the transmitter and receiver coils, the frequency of the primary field, and the bulk electromagnetic properties of the subsurface. It is important to understand that each FDEM measurement is effectively a 'single-depth' response; therefore, FDEM results are indicative only of lateral subsurface variations.

The results of the FDEM survey at the three survey locations are presented on **Figure 9** through **Figure 11**.

5.1.3 Electrical Resistivity Tomography (ERT) [Provided by Olson]

In an ERT survey, an electrical current is injected into the ground through two electrodes. Voltages on the surface are measured using another pair of electrodes revealing the direction and amount of current flow in the subsurface. These data are interpreted in terms of the resistivity (bulk resistance to current flow) of the earth materials.

ERT data at this site were acquired using a dipole-dipole electrode array configuration for mapping relatively shallow lateral variability with high resolution. The data were collected using an IRIS SYSCAL Pro system. For each line section, 72 to 96 electrodes were deployed at 16 foot intervals for a total of 1200 feet (Site A) and 1500 feet (Site C), respectively. A 12-volt external battery provided the current transmitted into the electrode arrays.

The results of the ERT survey at the two survey locations are presented on **Figure 12**, and **Figure 13**.

5.1.4 Multi-Channel Analysis of Surface Waves (MASW) [Provided by Olson]

Active and passive MASW surveys were conducted at each study area to analyze the velocities of surface waves and shear waves. The observed velocities are indicators of the degree of hardness of the subsurface material (i.e. bedrock or cemented alluvium).

Using a Geometrics Geode 24-channel seismograph with 24 4.5 Hz vertical component geophones placed at 10 foot intervals, MASW data were acquired using an active seismic source consisting of a sledgehammer impacting a plastic strike plate. Shot points were located every 30 feet, beginning with a 30 foot off-end shot at the beginning of each line. Acquisition parameters of the seismic system for the active MASW methods comprised of stacked 2 second records at a 0.125 millisecond (ms) sample rate. Passive MASW data were acquired as well, using acquisition parameters comprised of fifteen 30-second records with a 2 ms sample rate. There are no predefined source points for passive-source surface seismic surveys. Instead, the method uses ambient noise, or vibrational energy, that exists at a site. A sledgehammer impacting a plastic plate off the end of the line was used to add extra signal to the passive measurement to ensure maximum depth of penetration.

The results of the MASW survey are plotted on the test hole logs included in **Appendix B** and are summarized on **Figure 14**.

5.2 SURFACE INFILTRATION TESTING

LRE selected 7 locations to conduct surface infiltration testing based on the results of the TDEM and FDEM survey. The purpose of the infiltration testing was to evaluate the permeability of the near surface soils. The infiltration testing targeted both electrically resistive (coarse grained) and conductive (fine grained) areas to attempt to correlate infiltration rates to electrical resistivity. Infiltration tests were conducted using double ring infiltrometers and following ASTM D3385-18. The tests were run for a duration of 4-hours or until a steady state infiltration rate was achieved. A summary of the infiltration results is presented in **Table 5-1**.

The steady state infiltration rates from double ring infiltrometers are not equivalent to the saturated hydraulic conductivity (k_s) of the surficial soils unless steady state infiltration with the water table is achieved. Because the water table at the sites is approximately 80 feet below ground surface (or deeper), steady state infiltration with the water table was not achieved. Therefore, the infiltration rates provided in table 5-1 are greater than that of the material's $k_{s.}$

Table 5-1 - Surface Infiltration Test Results

Material Tested	Infiltration Test Number	Steady State Infiltration Rate (ft/day)	Geometric Mean - Steady State Infiltration Rate (ft/day)	Arithmetic Mean - Steady State Infiltration Rate (ft/day)
Older Alluvium Terraces	I-1	0.6	2.0	3
	I-2	2.1		
	I-3	6.3		
Younger Alluvium	I-4*	0.3	2.7	5.3
	I-5	13.5		
	I-8	3.6		
	I-9	3.8		
*Near surface deposits at I-4 are clays and the soil gradation likely dominated the low permeability test result.				

5.3 TEST HOLE DRILLING AND DOWNHOLE PERMEABILITY TESTING

LRE selected 3 locations to advance test holes and conduct downhole permeability testing. The purpose of the test holes were to: (1) characterize the lithology, (2) conduct downhole permeability testing to characterize the unsaturated aquifer material, and (3) provide calibration data for the geophysical surveys. Lithology logs and permeability testing summaries of the test holes are included in **Appendix B.** The test hole locations are shown on **Figure 1**.

5.3.1 Drilling and Lithological Logging

Test holes were drilled via the sonic method. The sonic drilling method consists of advancing an inner core barrel and an outer drive casing to obtain a continuous core sample of the formation (inner core barrel) while maintaining the open borehole (outer drive casing). The drill rods are advanced using a high-frequency resonant energy that vibrates the casing and causes liquefaction of the unconsolidated material encountered. This method was chosen because it provides for continuous and relatively undisturbed sampling of the test hole typically with 100% sample recovery. This allows for detailed lithological logging of the entire borehole. A summary of the lithology observed during drilling is presented in **Table 5-2**.

Table 5-2 - Test Hole Lithology Summary

Test hole	Total Depth	Static Water Table	Depth to Bedrock	Lithology
O-1	80 feet	Not encountered	Not encountered	• Loose to well cemented sand and clay • Dry to depth • Frequent calcium carbonate precipitate • Varying degrees of cementation with some samples having the strength and appearance of weak sandstone • Massive bedding to very thin bedding (distinct horizontal structure) at different depths • Drilling was more difficult than typical for unconsolidated sands and clays
O-4	60 feet	Not encountered	Not encountered	• Same as O-1 except with generally higher cementation • Driller noted that the rig response was typical to sandstone and other consolidated deposits
O-5	85 feet	69 feet	81 feet	• Loose to weakly cemented gravel, sand and clay • Shallow samples were moist, moisture decreased with depth until static water level was reached • Typically massively bedded with infrequent distinct horizontal structure (very thinly to thinly bedded) • Zones with a distinct horizontal structure generally correlate with zones of weak cementation • Blue shale and sandstone (Denver Formation) encountered at 81 feet.

5.3.2 Downhole Permeability Testing

Downhole permeability testing was conducted using constant-head and falling-head test methods. The following steps were followed during permeability testing:

1. The outer drive casing (6-inch diameter) was advanced to the top of the desired test interval.
2. The inner core barrel casing (4-inch diameter) was advanced to the bottom of the test interval – approximately 5 to 10 feet below the outer casing. The soil core and inner casing were then removed.
3. A perforated PVC access tube was advanced to near the bottom of the test hole.
4. A data logging pressure transducer was then placed inside the PVC access tube.
5. Water was pumped into the test hole.
6. The inflow rate was modified to maintain a constant head at a level as close as possible to the top of the test interval.
7. Metered water supply was poured into the feed pipe until the water level and flow rate stabilized. The flow rate required to maintain a constant-head within the test interval was recorded and used for interval permeability calculations.
8. Once the constant-head test was completed, the water level decline rate (falling head) was monitored for use in interval permeability calculations.
9. If a constant head could not be maintained at the minimum pump/meter flow rate (less than approximately one to two gallon per minute), the test was switched to the falling head method.
10. During a falling-head test, the casing was filled with water to a depth of approximately 10 feet above the test interval and the decline in head was monitored for at least 10 minutes.

The hydraulic conductivity of the subsurface material was then calculated from the constant- head and falling-head test data using methodology presented in the Bureau of Reclamation 2001 Engineering Geology Field Manual, Chapter 17 (USBR, 2001).

For the constant-head test, flow rate and water level were continuously monitored until both stabilized. The "Gravity Permeability Test Method 1" (USBR, 2001) was used to determine the saturated hydraulic conductivity within intervals where a stable flow rate and water level were observed. The equation is as follows:

$$K = \frac{2Q}{(C_s + 4)r\,T_u}$$

Where:
K = Hydraulic conductivity (ft/s)
Q = Flow rate into the test hole (ft^2/s)
C_s = Conductivity coefficient
r = Radius of the test section (ft)
T_u = Distance from the water surface in the test interval to the static water level (ft)

For the falling-head test, the water level decline rate was continuously monitored and the saturated hydraulic conductivity was calculated using the "Falling-Head Test Method for tests above the static water table" (USBR, 2001). The equation is as follows:

$$K = \frac{r_1^2}{2l\Delta t}\left[\frac{sinh^{-1}\left(\frac{l}{r_e}\right)}{2} x\, ln\left(\frac{2H_1 - l}{2H_2 - l}\right) - ln\left(\frac{2H_1H_2 - lH_2}{2H_1H_2 - lH_1}\right)\right]$$

Where:
K = Hydraulic conductivity (ft/s)
r_1 = Inside radius of the drop pipe (ft)
r_e = Effective radius of the test section (ft)
Δt = Time intervals (seconds)
l = Length of the test section (ft)
$sinh^{-1}$ = Inverse hyperbolic sine
ln = Natural Logarithm
H = Length of water column from bottom of test interval to water surface in standpipe (ft) at time of measurements

The average calculated saturated hydraulic conductivity from each interval of the three test holes is presented in **Table 5-3**.

6 DATA INTERPRETATION AND EVALUATION OF INVESTIGATION METHODS

The results of the field investigation generally correlate with the delineation between the younger alluvium (Holocene age Piney Creek and Post-Piney Creek Alluvium) and older alluvium (Pleistocene age). See page 13 and **Appendix A** for details on the general geologic background of these units. Test holes O-1 and O-4 were drilled on topographic highs and in the older alluvium. In general, the subsurface materials observed at these locations were weakly to well cemented, dry, and were interpreted to have a moderate to low permeability. Test hole O-5 was drilled in a topographic low and through the younger alluvium. The O-5 subsurface materials observed were loose to very weakly cemented, moist, and interpreted to have a moderate to high permeability.

6.1 SONIC TEST HOLE DRILLING RESULTS

The layering of all the alluvial deposits encountered is complex with frequently alternating beds of sand, clay, sandy clay, and clayey sand. The complex layering was characterized in continuous core samples from the sonic drilling method. The continuous sampling allowed for detailed logging of the lithology and the identification of thin bedding. However, the thin bedding and frequently alternating beds was not captured in the geophysical surveys.

Table 5-1 - Downhole Permeability Testing Results and Interpretation

Test hole	Top (ft bgs)	Bottom (ft bgs)	Saturated Hydraulic Conductivity (ft/day)	Method	Notes
O-1	10	20.5	0.6	Falling Head	Could not maintain a constant head within the flow rate limitations.
	20	30.2	11	Constant Head	
	30	40	11	Constant Head	
	40	49.4	0.1	Falling Head	Could not maintain a constant head within the flow rate limitations.
	50	60.5	7	Constant Head	
	59.7	70.5	0.2	Falling Head	Could not maintain a constant head within the flow rate limitations.
	69.7	80.5	50	Constant Head	Potentially hit water near the base of the borehole, at approximately 79 - 80 feet.
	Geometric Mean		**2.4**	**ft/day**	
O-4	9.9	20.5	0.045	Falling Head	Could not maintain a constant head within the flow rate limitations.
	19.9	30.2	10	Constant Head	
	29.8	40	0.02	Falling Head	Could not maintain a constant head within the flow rate limitations.
	39.8	50.5	0.009	Falling Head	Could not maintain a constant head within the flow rate limitations.
	49.8	60.5	0.081	Falling Head	Could not maintain a constant head within the flow rate limitations.
	Geometric Mean		**0.09**	**ft/day**	
O-5	9.8	20.5	0.3	Falling Head	Could not maintain a constant head within the flow rate limitations.
	19.8	30	17	Constant Head	
	29.8	40	23	Constant Head	
	39.8	50	8	Constant Head	
	50	60	14	Constant Head	
	59.8	70	235	Constant Head	Water table at 66-69 feet below ground surface. Only test in saturated zone
	Geometric Mean		**12.1**	**ft/day**	

6.2 ELECTROMAGNETIC SURVEY RESULTS

6.2.1 Time Domain Electromagnetic Survey Results

The TDEM survey was used to record variations in electrical resistivity/conductivity data (i.e. due to changes in lithology and/or moisture) with depth to assess vertical layering. As shown in the composite lithology logs (**Appendix B**), there is no apparent correlation between the fine-grained beds and electrically conductive zones, or the coarse grained beds and resistive zones. The likely cause of this mismatch is the large 40-foot loops used during the TDEM survey. The larger loops allow for deeper depths of investigation but reduce the vertical resolution. Future TDEM surveyors should consider using a smaller loop-size to increase data resolution to characterize the vertical heterogeneity of the shallow alluvial deposits.

KEY TAKEAWAY

FUTURE TDEM SURVEYORS SHOULD CONSIDER USING A SMALLER LOOP-SIZE TO INCREASE DATA RESOLUTION TO CHARACTERIZE THE VERTICAL HETEROGENEITY OF THE SHALLOW ALLUVIAL DEPOSITS.

6.2.2 Frequency Domain Electromagnetic Survey Results

FDEM surveys were also conducted to record changes in electrical resistivity at relatively shallow depths (effective depths of up to 30 feet). The results of the FDEM survey correlate well with the thickness of sand observed in the top 10 and top 30 feet at the test holes. **Table 6-1** shows a comparison of the logged feet of sand and the FDEM Resistivity. Test hole O-1 had the greatest thickness of logged sand and the highest electrical resistivity. O-4 had less sand and a lower resistivity and test hole O-5 had the least amount of sand and correspondingly the lowest measured electrical resistivity.

KEY TAKEAWAY

CEMENTATION OF THE ALLUVIUM APPEARS TO HAVE NO INFLUENCE ON THE FDEM RESULTS.

FDEM appears to be an effective method for locating zones of relatively coarse and fine material in the top 30 feet of the subsurface. This could be an effective tool for relative comparison when siting the best location for an infiltration basin in a target parcel. It is important to note that cementation of the alluvium appears to have no influence on the FDEM results and FDEM should only be used to target beneficial infiltration locations if the degree of cementation of the particles has been confirmed with another method.

Table 6-2 - Comparison of FDEM Results and Observed Lithology

Test hole	Feet of Sand[1] in Top 30 Feet	Feet of Sand[1] in Top 10 Feet	FDEM Resistivity (Ohm-m)
O-1	17.5	9.5	24.9
O-4	15	5	15.1
O-5[2]	13	0	11.6

1. **Defined as material logged as sand with less than 12% fines (SW, SP, SW-SC, SP-SC). Clayey sands (SC) were not counted.**

2. **Test hole O-5 was off the path of the FDEM and the results are from a nearby location**.

6.2.3 Effects of Moisture Content/ Saturation on TDEM and FDEM Results

The degree of soil saturation does not appear to have had a significant impact on the TDEM and FDEM resistivity values. In general, both the TDEM and FDEM indicated more electrically-resistive materials (i.e. coarse materials) in the topographic lows and more conductive materials (i.e. fine material) near the topographic highs. The trend is not perfect with some variations and areas of more conductive material in the topographic highs. As we observed in test hole O-5, the materials in the topographic lows appear to have a higher degree of saturation while the materials on the topographic highs were dry with no moisture. If the saturation was greatly influencing the conductivity of the materials, then it is expected that the materials in the topographic lows would be more conductive when they were actually observed to be more resistive. This indicates that the material gradation (i.e. coarse versus fine) is driving the observed electrical resistivity/conductivity.

KEY TAKEAWAY

THE DEGREE OF SOIL SATURATION DOES NOT APPEAR TO HAVE HAD A SIGNIFICANT IMPACT ON THE TDEM AND FDEM RESISTIVITY VALUES.

6.3 ELECTRICAL RESISTIVITY TOMOGRAPHY RESULTS

The ERT survey was conducted to measure the electrical resistivity/conductivity of a relatively shallow vertical section, but with higher resolution than the TDEM survey. However, the ERT survey did not appear to produce significantly more detailed results than the TDEM survey. The fine layering of the alluvial material was not captured in the ERT results, which indicated relatively massive deposits that were not observed in the exploratory boreholes.

KEY TAKEAWAY

THE FINE LAYERING OF THE ALLUVIAL MATERIAL WAS NOT CAPTURED IN THE ERT RESULTS.

6.4 MULTI-CHANNEL ANALYSIS OF SURFACE WAVES (MASW) RESULTS

The effect of cementation was most clearly picked up with the MASW survey. As seen in the composite lithology logs, the areas of relatively high shear wave velocity tend to correlate with zones of observed cementation and high dry strength. **Figure 14** shows the shear wave velocities in profile at the three test holes. The shear wave velocities appear to be higher at O-1 and O-4 relative to O-5, particularly between the depths of 20 to 60 feet below ground surface. The average shear wave velocities at O-1 and O-4 whre 905 and 847 ft/s, respectively. These values are significantly greater than the average shear wave velocity of 808 ft/s at O-5. The relatively higher shear wave velocities of the cemented materials make MASW (or other seismic methods) an appropriate tool for delineating cemented versus loose materials. The cemented, older alluvial deposits had, on average, a shear wave velocity 40 to 100 ft/s greater than the relatively loose deposits.

KEY TAKEAWAY

THE HIGHER SHEAR WAVE VELOCITIES OF THE CEMENTED MATERIALS MAKE MASW (OR OTHER SEISMIC METHODS) AN APPROPRIATE TOOL FOR DELINEATING CEMENTED VERSUS LOOSE MATERIALS.

MASW COULD ALSO BE AN APPROPRIATE METHOD FOR ESTIMATING BEDROCK DEPTH BECAUSE OF ITS DENSITY AND RESULTING HIGH SHEAR WAVE VELOCITIES.

MASW could also be an appropriate method for estimating bedrock depth because of its relatively high density (consolidation and cementation). O-5 is the only test hole that encountered bedrock, where it was observed at 80 ft bgs. This correlates well with the MASW results that increase to the test hole maximum value of greater than 1,500 ft/s at a depth of approximately 78 feet.

The one-dimensional MASW results indicate that two-dimensional seismic profiles may provide appropriate characterization of the distribution of cemented aquifer material and bedrock depth across larger areas.

The MASW data did not show significant correlation to the grain size of materials observed in test hole samples.

6.5 DOWNHOLE PERMEABILITY TESTING

The interpretation of saturated hydraulic conductivity from the infiltration tests is known to be uncertain. The interpreted values are meant to give a relatively high or relatively low permeability result and the exact value is not suitable for engineering design purposes. Stephens, 1979 indicates that the USBR method may result in k_s values that vary up to 160% from the true value.

Additionally, the interpreted k_s from the falling head test is correlated to the driving head, which can be controlled by the amount of water above the testing area. The interpreted k_s values from the-falling head tests were often up to an order of magnitude lower than the interpreted k_s values from a constant-head test in the same interval. Despite this uncertainty, the USBR method seems to be the best available method for interpreting borehole permeability results in the unsaturated alluvium.

KEY TAKEAWAY

DOWNHOLE PERMEABILITY TESTING IS AN EFFECTIVE TOOL FOR QUALITATIVE CHARACTERIZATION OF SUBSURFACE MATERIAL PERMEABILITY.

The main uncertainty in permeability or infiltration testing is the characterization of the wetting front. Characterization of a wetting front would allow for the application of more complex vadose zone numerical models and a more accurate interpretation of k_s. However, in downhole permeability testing, characterization of the wetting front is difficult and therefore, the USBR method is still the best tool available. Despite the method uncertainties, the downhole permeability testing is an effective tool for qualitative characterization of subsurface material permeability and is a good tool for comparing the relative permeability of alluvial layers. In the areas investigated for this project, the distinct differences in permeability due to cementation were evident in the permeability testing results; and the borehole permeability testing was an effective tool for broadly characterizing the effect of cementation on permeability.

6.6 SURFACE INFILTRATION TESTING

The surface infiltration tests provide an estimate of potential infiltration rates in the shallow subsurface. The observed infiltration rates are likely to vary from actual infiltration rates in a constructed basin due to the effects of deeper soil horizons, long-term operations achieving steady conditions with the groundwater table, lateral heterogeneity and clogging over time, none of which are considered in the double-ring infiltrometer tests. A long-term infiltration test in a test basin is a more suitable method for estimating long-term infiltration rates and basin design. The double-ring infiltrometer tests are an effective test for targeting soils with a relatively high infiltration capacity. Saturated hydraulic conductivity may be estimated from the infiltration rates, but there is uncertainty in these estimates due to the effects of unsaturated soil physics on the infiltration rates. These effects are difficult to accurately account for without a well-characterized wetting front and understanding of the subsurface anisotropy. Therefore, the tests are best used for approximating relative infiltration rates instead of estimating absolute k_s values.

KEY TAKEAWAY

A LONG-TERM INFILTRATION TEST IN A TEST BASIN IS A MORE SUITABLE METHOD FOR ESTIMATING LONG TERM INFILTRATION RATES AND BASIN DESIGN.

6.7 ALLUVIAL AQUIFER CEMENTATION

The young and older alluviums were not significantly different with regard to material gradation with both being composed of interlayered sand and clay with some gravel. The distinct difference between the two ages of alluvium is the degree of cementation and the horizontal thinly bedded structure of the cemented units. Calcium carbonate cement has the potential to fill the void space of the alluvium resulting in a lower effective porosity and lower water storage capacity. The cementation also results in lower permeability, which reduces the rate at which the aquifer could be recharged through surface infiltration basins. A reduction in permeability of the cemented units is evident in the downhole permeability testing data. The geometric mean of the interpreted permeability at O-1 and O-4 is 20% and 1% of that at O-5, respectively.

For future siting of infiltration basins, it is important to know whether the cementation or the alluvium composition (i.e. sand versus clay content) has a greater impact on the material permeability. In general, coarser deposits have a high permeability and fine deposits have a low permeability. Therefore, it would be anticipated that the interpreted hydraulic conductivity from the permeability tests would correlate to the thickness of sand deposits in the 10-foot test interval.

A correlation between the interpreted hydraulic conductivity from each permeability test and the thickness of logged sand in the 10 foot test interval is presented on **Figure 15**. Each data point is representative of one of the permeability tests conducted (see **Table 5-3**). The lines are the logarithmic best fit for each set of permeability tests grouped by test hole. The correlation coefficient r-squared (R^2, unitless) for the permeability tests at test hole O-4 is 0.0023. This is considered a poor fit, therefore the permeability of the material does not appear to be correlated to the gradation or relative coarseness of the alluvium. The R^2 of the permeability tests at test hole O-1 is 0.1008 which indicates a weak correlation of the permeability to the gradation or relative coarseness of the alluvium. Finally, the R^2 of the permeability tests at O-5 is 0.5971 which indicates that there is a statistical correlation between the coarseness of the deposit and the permeability. The weak correlation between gradation and permeability in the older alluvium indicates that the permeability of these units is primarily controlled by the degree of cementation of the deposits. In the younger alluvium, where the alluvium is not cemented, the permeability is controlled by the gradation of the deposits.

KEY TAKEAWAY

THE WEAK CORRELATION BETWEEN GRADATION AND PERMEABILITY IN THE OLDER ALLUVIUM INDICATES THAT THE PERMEABILITY OF THESE UNITS IS PRIMARILY CONTROLLED BY THE DEGREE OF CEMENTATION OF THE DEPOSITS. IN THE YOUNGER ALLUVIUM, WHERE THE ALLUVIUM IS NOT CEMENTED, THE PERMEABILITY IS CONTROLLED BY THE GRADATION OF THE DEPOSITS.

6.8 AQUIFER LAYERING

As observed in the lithologic logs, complex layering and frequently alternating beds of sand, clay, sandy clay, and clayey sand are present in each of the test holes. The effect of the fine structure on aquifer recharge is uncertain at this time. The lateral continuity of thin clay beds could not be determined with the data collected. A continuous thin clay bed could reduce the rate of groundwater recharge. If the clay beds are inter-fingered or spatially limited, sufficient pathways for recharge water would be present and the observed thin beds would have limited effect on the ability to recharge the aquifer with infiltration basins.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 FIELD METHOD CONCLUSIONS

We co-located field method testing sites so that results from different methods could be compared. We concluded the following about the various field investigation methods tested:

- Surface Geophysical surveys are a reliable means to characterize large areas of the subsurface, but should be locally calibrated and verified by exploratory boreholes. The geophysical testing results can provide valuable information for siting exploratory boreholes.

- The exploratory borehole lithology observations were the most detailed and accurate characterizations of subsurface materials, and were used as the baseline data to compare other results. The sonic drilling method provided high quality, continuous soil core samples necessary for characterizing the high degree of vertical heterogeneity of the lithology.

- FDEM interpreted results closely matched the exploratory borehole observed net sand thickness in the top 30 feet of the subsurface. FDEM results provide a reliable, relative characterization of the bulk grain size in the top 30 feet of unsaturated alluvial deposits.

- TDEM results did not have the resolution necessary to provide useful subsurface characterization for this project. The method could be adapted to have multiple passes with different equipment configurations (coil sizes). With proper configuration, TDEM may provide a reliable, relative characterization of the grain size and layering in unsaturated alluvial deposits.

- MASW interpreted results closely matched the borehole aquifer cementation and bedrock depth observations. MASW results provided a relative measure of cementation and bedrock depth in unsaturated alluvial deposits.

- ERT results were unreliable and are not recommended for future investigations.

- The interpretations of saturated hydraulic conductivity from the surface and downhole infiltration tests are known to be uncertain. Therefore the interpreted values are meant to give a relative, qualitative permeability estimate and not a precise value suitable for engineering design purposes.

- Surface double-ring infiltrometer testing provided a direct measurement of infiltration rates into surficial soils.

- The methods presented here are not exhaustive, and additional field investigation technologies and methods should continue to be considered.

7.2 LOST CREEK BASIN HYDROGEOLOGIC CHARACTERIZATION CONCLUSIONS

We have made the following conclusions regarding the hydrogeologic characteristics of Lost Creek Basin as they relate to underground water storage planning:

- The alluvial deposits are vertically variable with frequent very thin to thick alternating beds of sand, clay, clayey sand, and sandy clay with some gravelly areas. Intermediate clay beds were observed in all three test holes. These intermediate clay beds have the potential to represent challenges to groundwater recharge. The lateral continuity of these beds and their potential effect on infiltration rates is important and should be better characterized.

- Near surface (shallower than 10 feet below ground surface) fine grained material may inhibit infiltration and should be specifically investigated, even in areas where the deeper deposits are permeable.

- Significant cementation of the alluvial aquifer vadose zone material was observed in two of three test holes.

- The degree of cementation influences permeability and porosity of the alluvial deposits and is a key planning consideration for underground storage at this location.

- Older alluvial deposits generally form topographic highs (terraces), are weakly to well cemented, and display a low to moderate permeability that is less conducive to infiltration. In these older alluvial deposits, the permeability of the subsurface material is not correlated to the gradation and is controlled by the cementation.

- Younger alluvium exists in topographically low spots, was generally loose, poorly cemented, and displayed moderate to high permeability; which is more conducive to infiltration.

- These conclusions are specific to the areas of the Lost Creek Basin that were investigated but are likely applicable to underground storage planning in other alluvial aquifers of the South Platte River and its tributaries.

7.3 RECOMMENDATIONS

Planning of underground storage will benefit from a phased feasibility investigation approach starting with regional or basin-scale investigations followed by localized field investigation. We recommend the following for future feasibility studies of underground storage in the alluvial aquifers of the South Platte River and its tributaries.

7.3.1 Basin Scale or Regional Investigations

- The cementation of the older alluvial deposits is a critical underground storage consideration and is not identified in regional studies, such as the 2011 Lost Creek Basin Aquifer Recharge and Storage Study (CGS, 2011). The reduction in pore space and permeability due to cementation may result in a lower amount of available storage than previously characterized. A desktop study should be conducted to re-evaluate available storage and permeability in the aquifer assuming that the older alluvial deposits are moderately to well cemented.

- Field mapping should be used to refine the available surficial geology and soil maps with a focus on mapping the younger and older alluvial deposits.

- Two-dimensional seismic profiles may help to characterize the distribution of cemented aquifer materials over larger areas.

- Basin/regional scale investigations and underground storage planning may also benefit from three-dimensional geologic modeling and groundwater flow modeling.

- If the conclusions of this study continue to hold true with additional investigation, local field investigations for recharge potential should be focused in the younger Piney Creek and Post Piney Creek alluvial deposits.

7.3.2 Local or Parcel Scale Investigations:

- The potential effect of shallow clay layers in the younger alluvium and the lateral continuity of these clay layers should be further investigated.

- Future investigations should include longer term infiltration testing using test pits or pilot infiltration basins to better characterize realistic infiltration rates. These tests should include observations of the wetting front and changes in groundwater levels throughout the test.

- Future parcel scale investigations should utilize FDEM geophysical surveys to optimize the location of infiltration basins and to target the relatively coarse materials in the top 30 feet of the alluvium.

- Future investigation utilizing the TDEM geophysical method should modify the equipment configuration to investigate the shallower materials in greater resolution.

- Future site investigations should include characterization of alluvium cementation. We recommend the use of seismic geophysical methods (such as MASW) in combination with test holes to characterize the degree of cementation in the alluvium.

- Future local-scale investigations should consider additional methods for investigating the existence and impact of vertical layering and lateral continuity of layers.

- Three dimensional geologic modeling and vadose zone/groundwater modeling should be conducted to evaluate the recharge and associated recovery of recharge water

The results of this study continue to show that there is good potential for underground storage of water in the alluvial aquifers of the South Platte River and its tributaries. Using the recommended investigation methods presented herein will increase the success of underground storage projects.

8 REFERENCES

Bryant, B., McGrew, L.W., and Wobus, R.A., 1981, Geologic map of the Denver 1x2 degree quadrangle, north-central Colorado: U.S. Geological Survey, Miscellaneous Investigations Series Map I-1163.

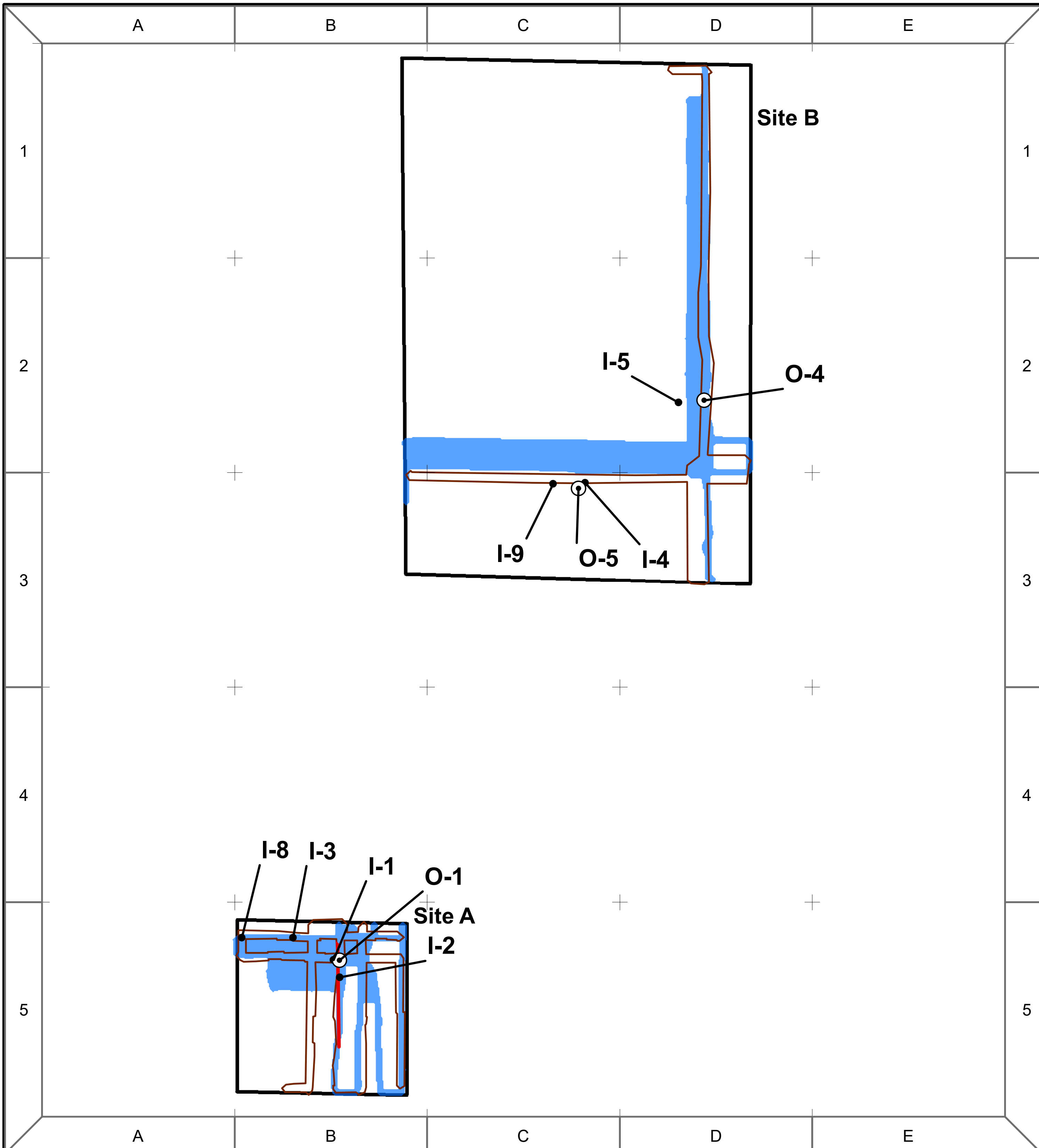
CGS, 2011. Lost Creek Basin Aquifer Recharge and Storage Study. Colorado Geological Survey. Prepared for the Lost Creek Groundwater Management District.

CGS, 2004. Artificial Recharge of Ground Water in Colorado - A Statewide Assessment. Colorado Geological Survey.

CWCB, 2007. SB06-193 Underground Water Storage Study. Colorado Water Conservation Board.

Stephens, Daniel B. 1979. Analysis of Constant Head Borehole Infiltration Test in the Vadose Zone. The University of Arizona. Dissertation-Reproduction.

USBR, 2001. Engineering Geology Field Manual. United States Bureau of Reclamation.



0 1,500 3,000

Feet

1:24,539

N

Sonic Test Hole / MASW Points

Surface Infiltration Tests

ERT Lines

TDEM Investigation Area

FDEM Investigation Area

Investigation Sites

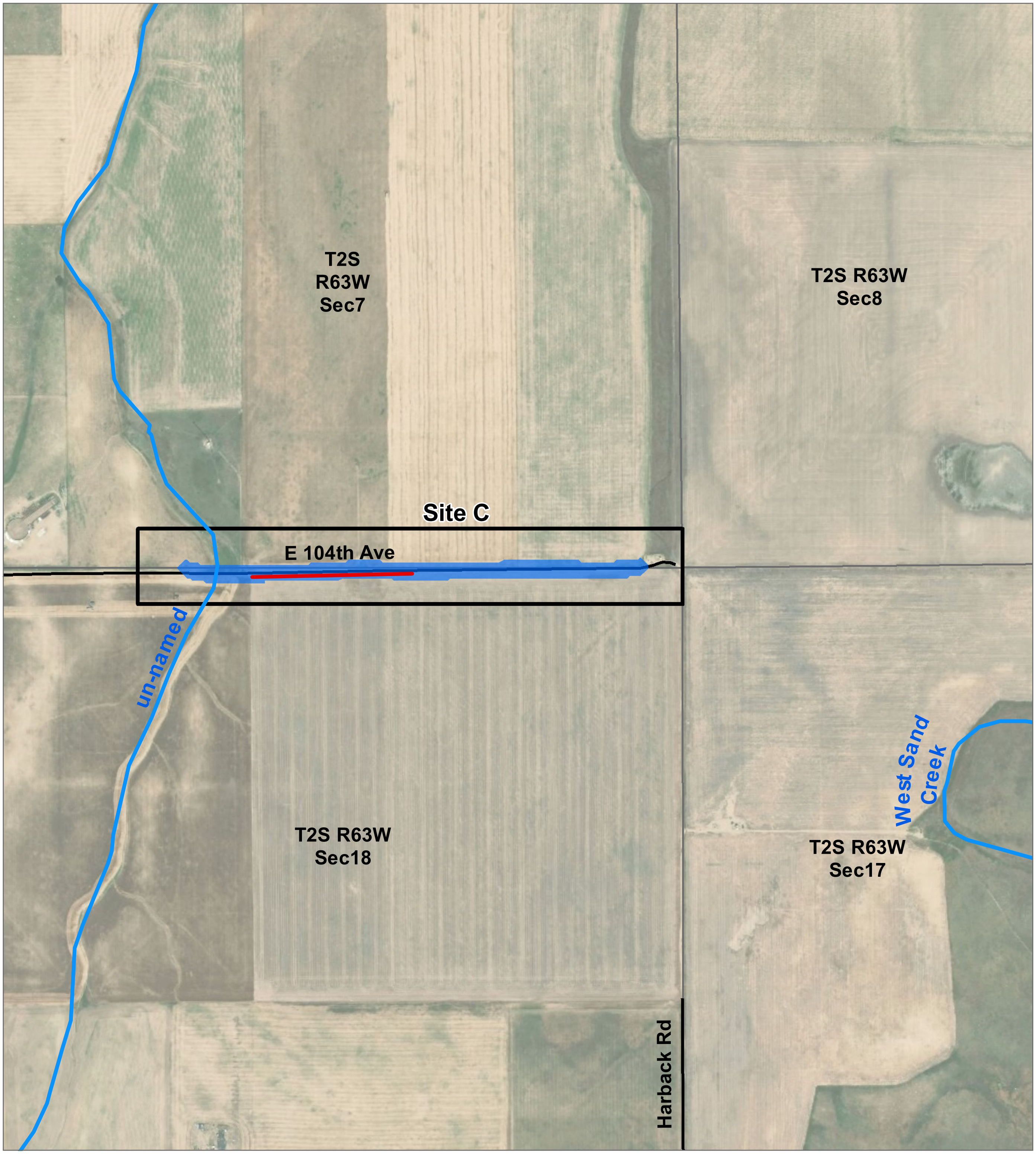
FIGURE 1

INVESTIGATION SITES AND METHODS

LeonardRice ENGINEERS, INC.

11/9/2018

Path: U:\1412AUW02_LCUSP\00_GIS\2018GDB\MXD\ReportDocumentsFinal\Fig01_Investigation_Sites_Methods_private_property.mxd



0 670 1,340

Feet

1:10,490

N

Sonic Test Hole / MASW Points

Surface Infiltration Tests

ERT Lines

TDEM Investigation Area

FDEM Investigation Area

Investigation Sites

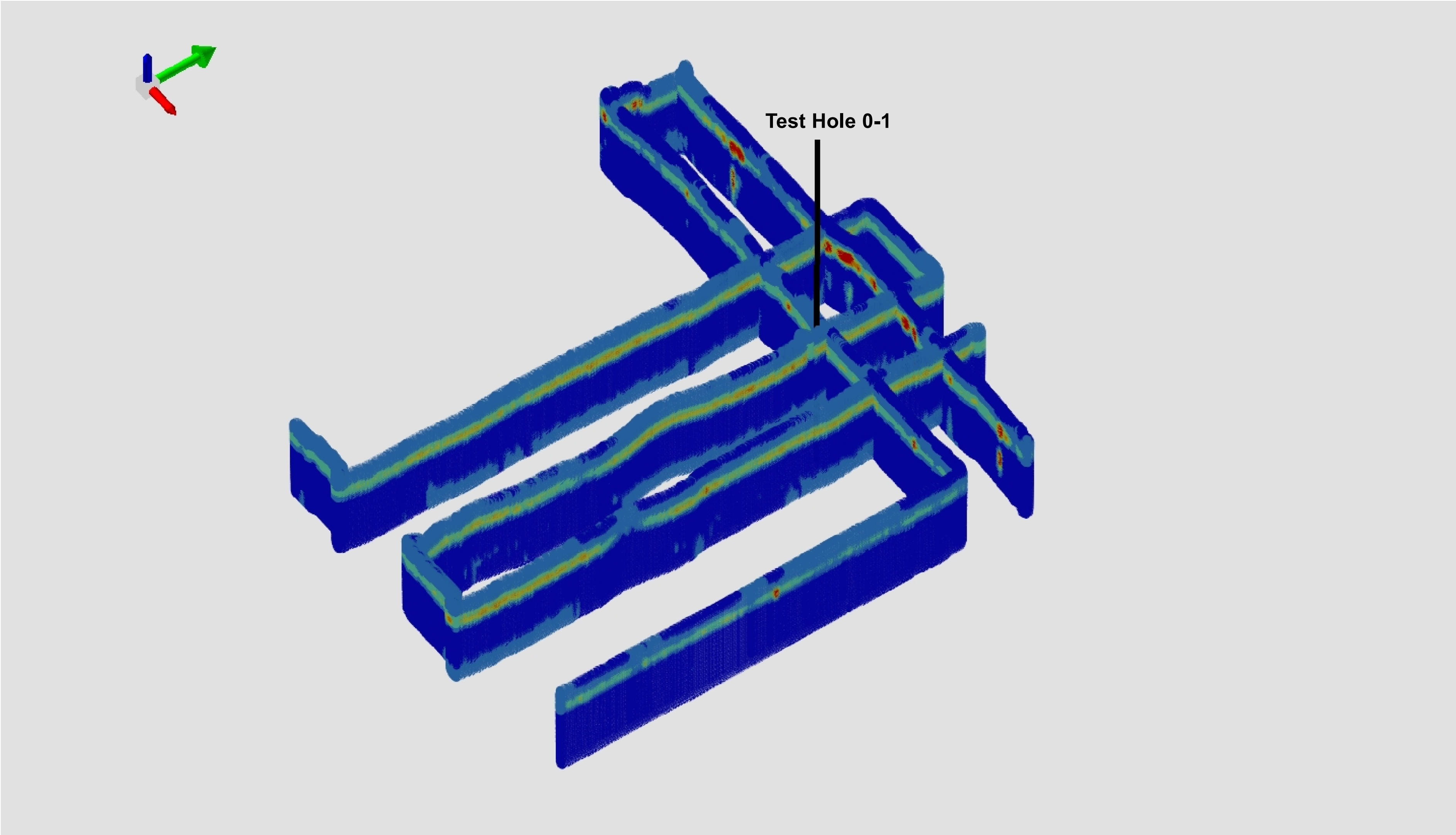
FIGURE 2

INVESTIGATION SITES AND METHODS PUBLIC RIGHT OF WAY

LeonardRice ENGINEERS, INC.

11/9/2018

Path: U:\1412AUW02_LCUSP\00_GIS\2018GDB\MXD\ReportDocumentsFinal\Fig02_Investigation_Sites_Methods_county_row.mxd



3X Verticle Exaggeration

Increasing grain size

Resistivity (Ohm-m)

-0.3 - 5.0
5.1 - 10.0
10.1 - 15.0
15.1 - 20.0
20.1 - 25.0
25.1 - 30.0

This product is for reference purposes only and is not to be construed as a legal document or survey instrument.

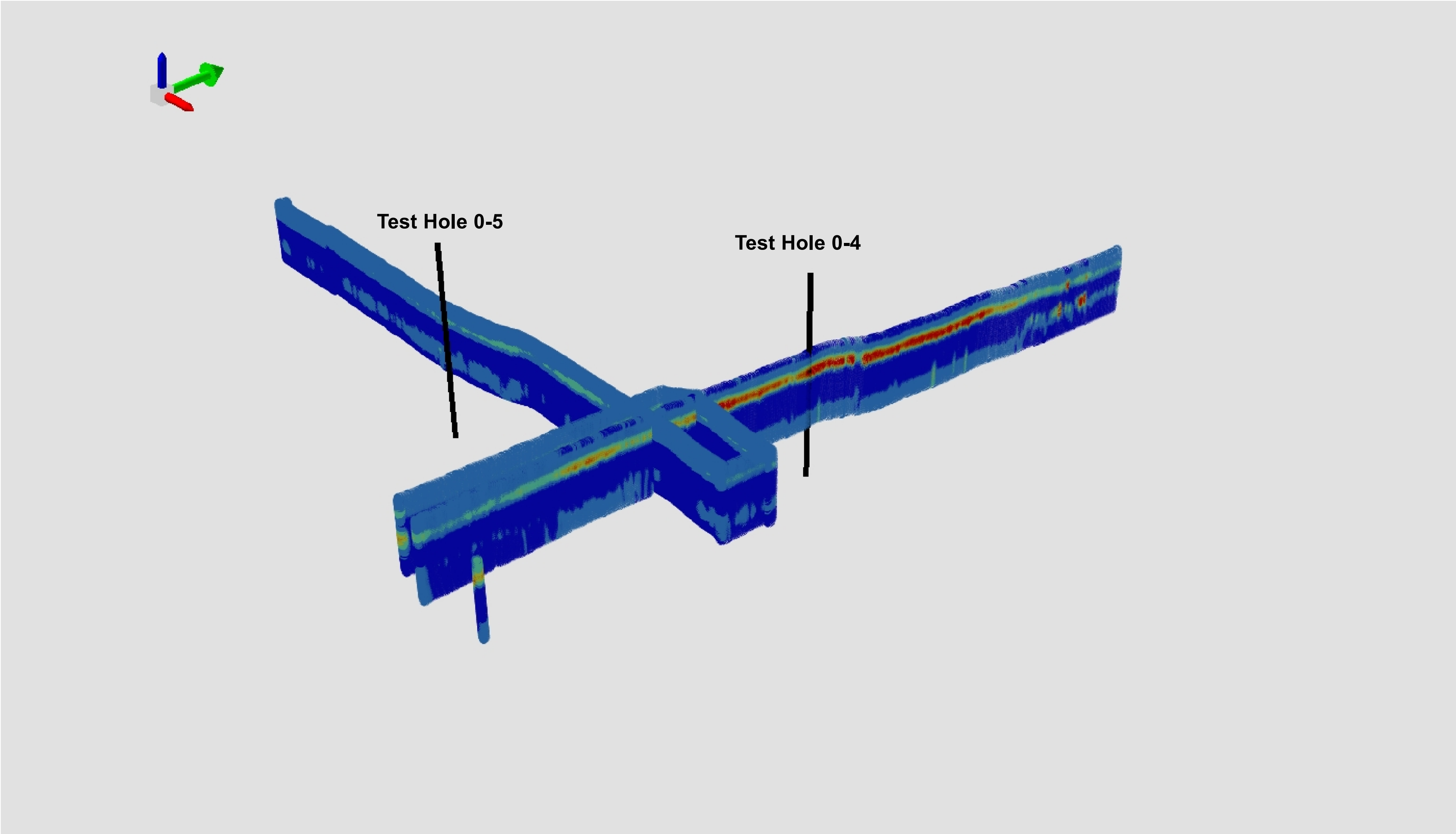
FIGURE 3

SITE A
TDEM INVERSION

LeonardRice ENGINEERS, INC.

1412AUW
11/9/2018

Path: U:\1412AUW\02_LCUSP\00_GIS\2018GDB\MXD\ReportDocumentsFinal\Fig03_SiteA_TDEM_Inversion.mxd



3X Verticle Exaggeration

Increasing grain size

Resistivity (Ohm-m)

-0.3 - 5.0
5.1 - 10.0
10.1 - 15.0
15.1 - 20.0
20.1 - 25.0
25.1 - 30.0

This product is for reference purposes only and is not to be construed as a legal document or survey instrument.

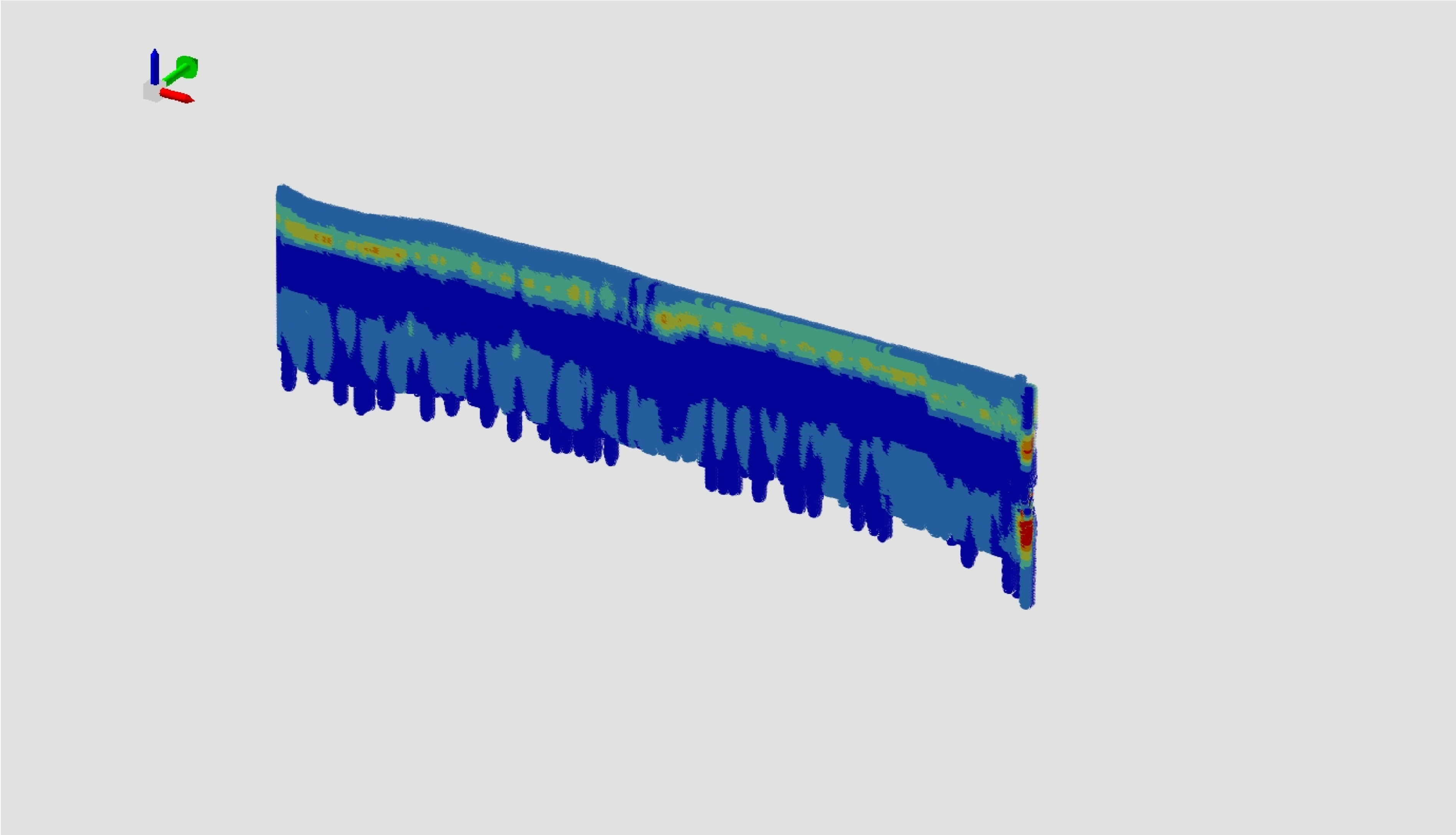
FIGURE 4

SITE B
TDEM INVERSION

LeonardRice ENGINEERS, INC.

1412AUW
11/9/2018

Path: U:\1412AUW\02_LCUSP\00_GIS\2018GDB\MXD\ReportDocumentsFinal\Fig04_SiteB_TDEM_Inversion.mxd



3X Verticle Exaggeration

Increasing grain size

Resistivity (Ohm-m)

-0.3 - 5.0
5.1 - 10.0
10.1 - 15.0
15.1 - 20.0
20.1 - 25.0
25.1 - 30.0

This product is for reference purposes only and is not to be construed as a legal document or survey instrument.

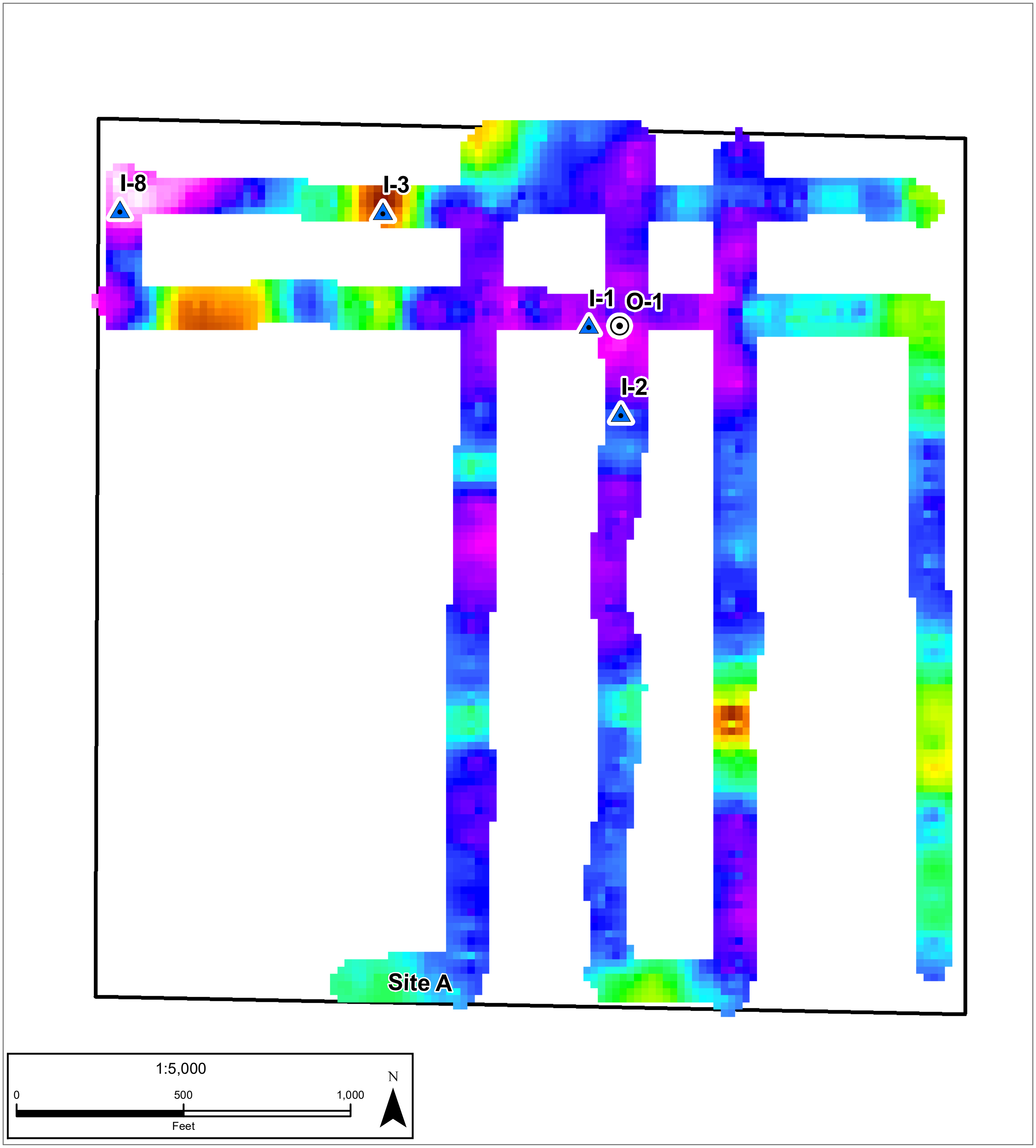
FIGURE 5

SITE C
TDEM INVERSION

LeonardRice ENGINEERS, INC.

1412AUW
11/9/2018

Path: U:\1412AUW\02_LCUSP\00_GIS\2018GDB\MXD\ReportDocumentsFinal\Fig05_SiteC_TDEM_Inversion.mxd



Surface Infiltration

Test Holes

Site Boundaries

Time Domain Electromagnetics (TDEM)

Response Amplitude (mV)

High : 1200 (Conductive, finer grained matarial)

Low : 600 (Resistive, coarser grained material)

Note: Symbology set to different scale than other figures

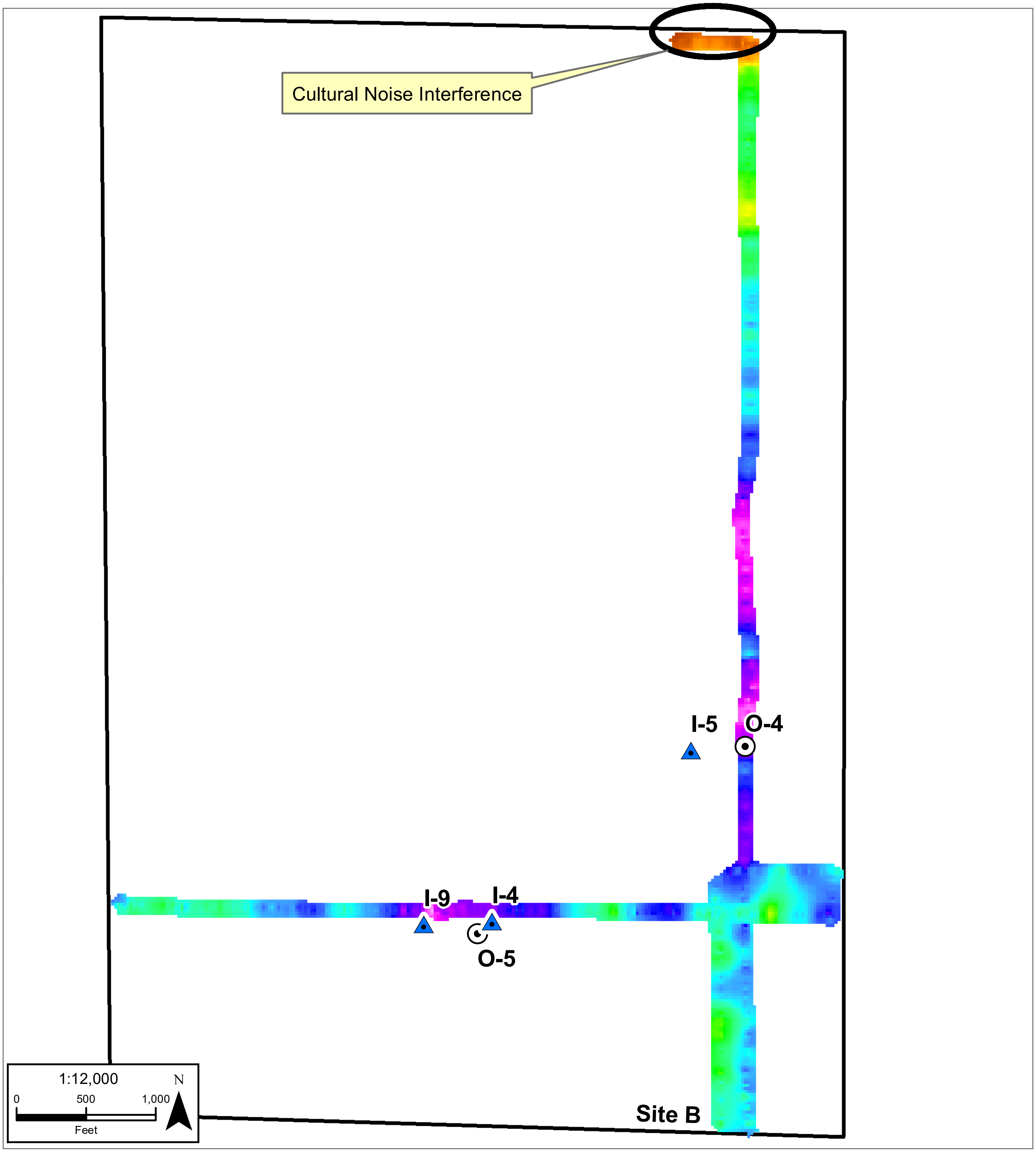
FIGURE 6

SITE A TIME DOMAIN ELECTROMAGNETICS

LeonardRice ENGINEERS, INC.

1427AUR
April 2018

Path: U:\1412AUW02_LCUSP\00_GIS\2018GDB\MXD\ReportDocumentsFinal\Fig06_SiteA_TDEM.mxd



Surface Infiltration

Test Holes

Investigation Site Area

Time Domain Electromagnetics (TDEM)

Repose Amplitude (mV)

High : 1200

Low : 500

Note: Symbology set to different scale than other figures

This product is for reference purposes only and is not to be construed as a legal document or survey instrument.

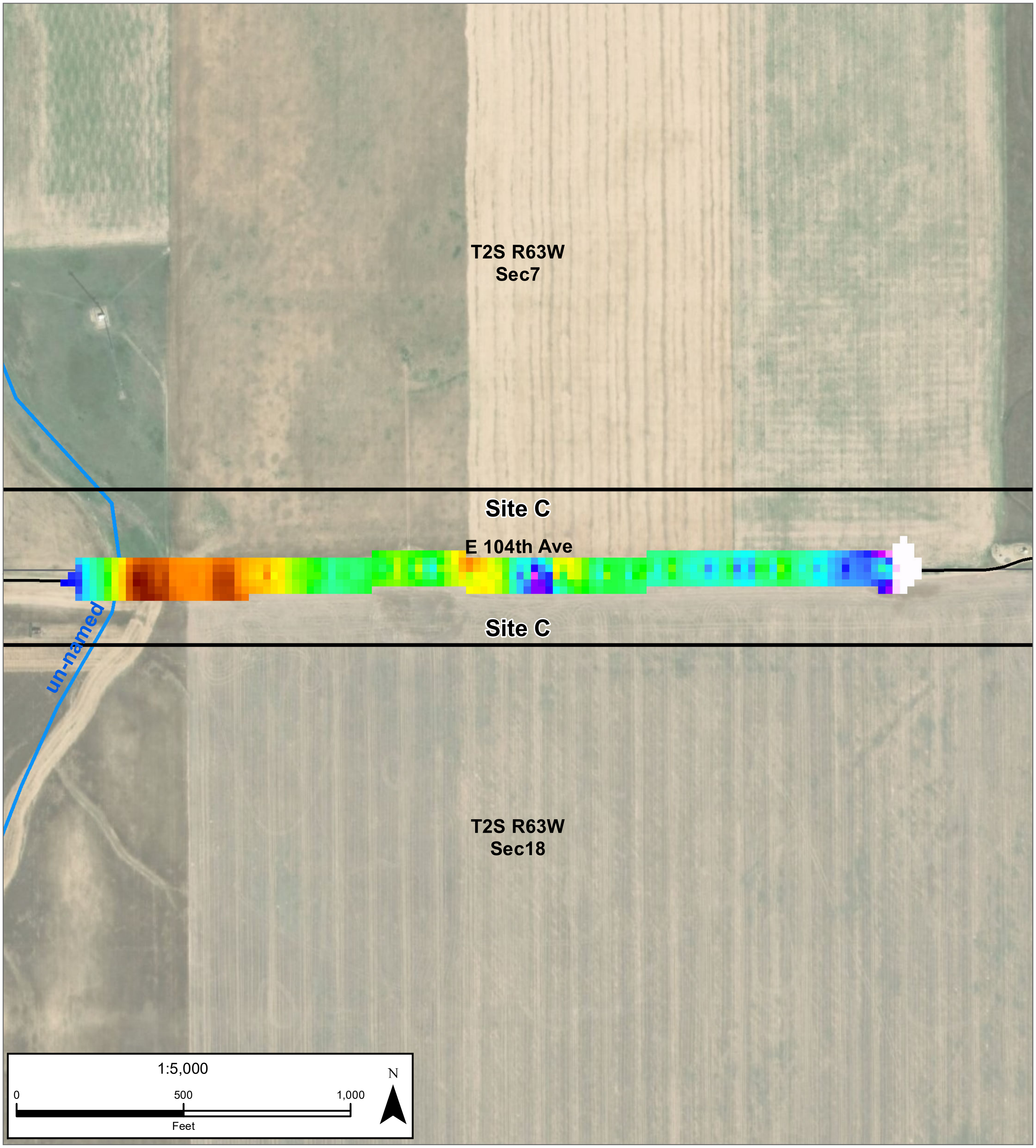
FIGURE 7

**SITE B
TIME DOMAIN
ELECTROMAGNETICS**

LeonardRice ENGINEERS, INC.

1427AUR
April 2018

Path: U:\1412AUW02_LCUSP\00_GIS\2018GDB\MXD\ReportDocumentsFinal\Fig07_SiteB_TDEM.mxd



Path: U:\1412AUW02_LCUSP\00_GIS\2018GDB\MXD\ReportDocumentsFinal\Fig08_SiteC_TDEM.mxd

Time Domain Electromagnetics (TDEM)

Response Amplitude (mV)

High : 1811

Low : 1500

Investigation Site Area

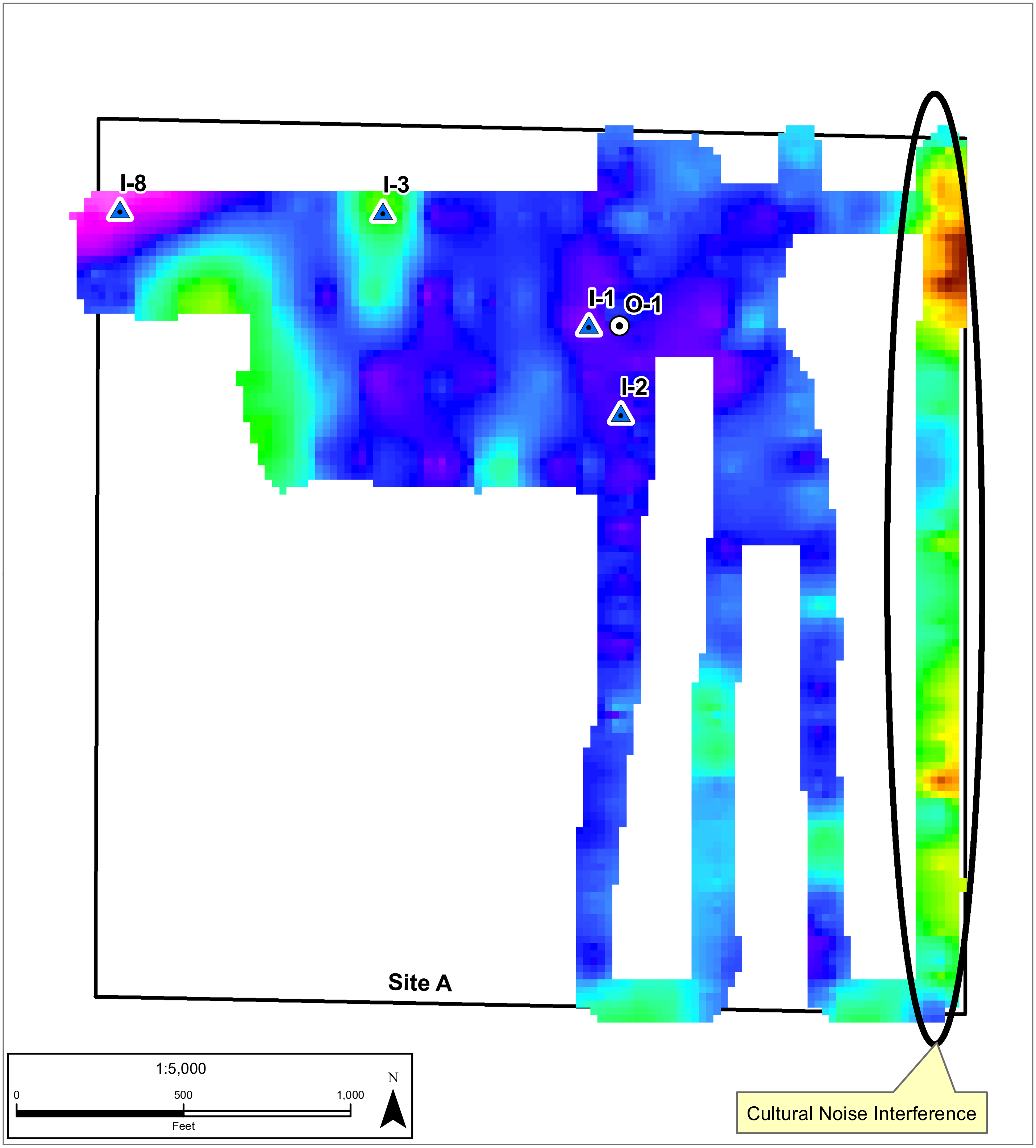
Note: Symbology set to different scale than other figures

FIGURE 8

SITE C
TIME DOMAIN
ELECTROMAGNETICS

LeonardRice ENGINEERS, INC.

1427AUR
April 2018



Surface Infiltration

Test Holes

Parcels

Frequency Domain Electromagnetics (FDEM)

Bulk Conductivity (mS/m)

High : 87

Low : 0

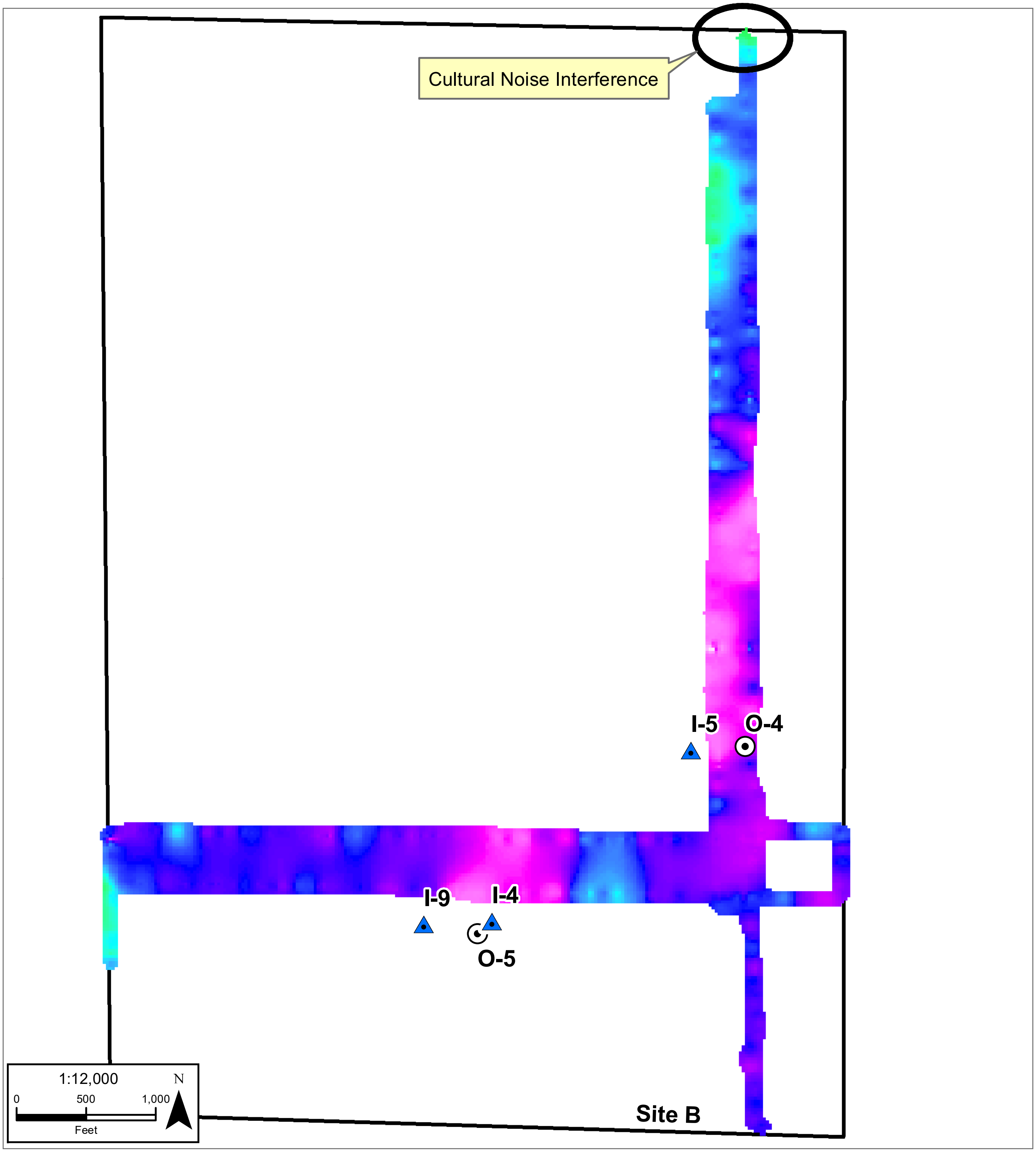
FIGURE 9

SITE A FREQUENCY DOMAIN ELECTROMAGNETICS

LeonardRice ENGINEERS, INC.

1427AUR
April 2018

Path: U:\1412AUW02_LCUSP\00_GIS\2018GDB\MXD\ReportDocumentsFinal\Fig09_SiteA_FDEM.mxd



Surface Infiltration

Test Holes

Site Investigation

Frequency Domain Electromagnetics (FDEM)

Bulk Conductivity (mS/m)

High : 87

Low : 0

FIGURE 10

SITE B FREQUENCY DOMAIN ELECTROMAGNETICS

LeonardRice ENGINEERS, INC.

1427AUR
April 2018

Path: U:\1412AUW02_LCUSP\00_GIS\2018GDB\MXD\ReportDocumentsFinal\Fig10_SiteB_FDEM.mxd

Site Investigation

Frequency Domain Electromagnetics (FDEM)

Bulk Conductivity (mS/m)

High : 87

Low : 0

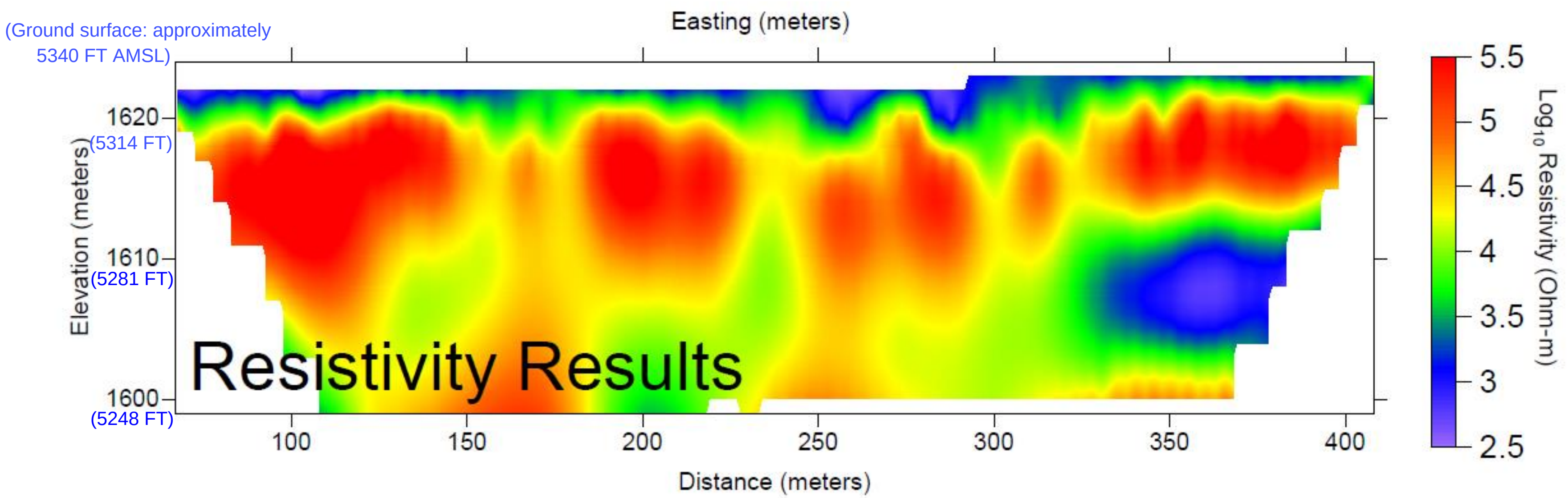
FIGURE 11

SITE C FREQUENCY DOMAIN ELECTROMAGNETICS

LeonardRice ENGINEERS, INC.

1427AUR
April 2018

Path: U:\1412AUW02_LCUSP\00_GIS\2018GDB\MXD\ReportDocumentsFinal\Fig11_SiteC_FDEM.mxd



DATE:
6/20/2017

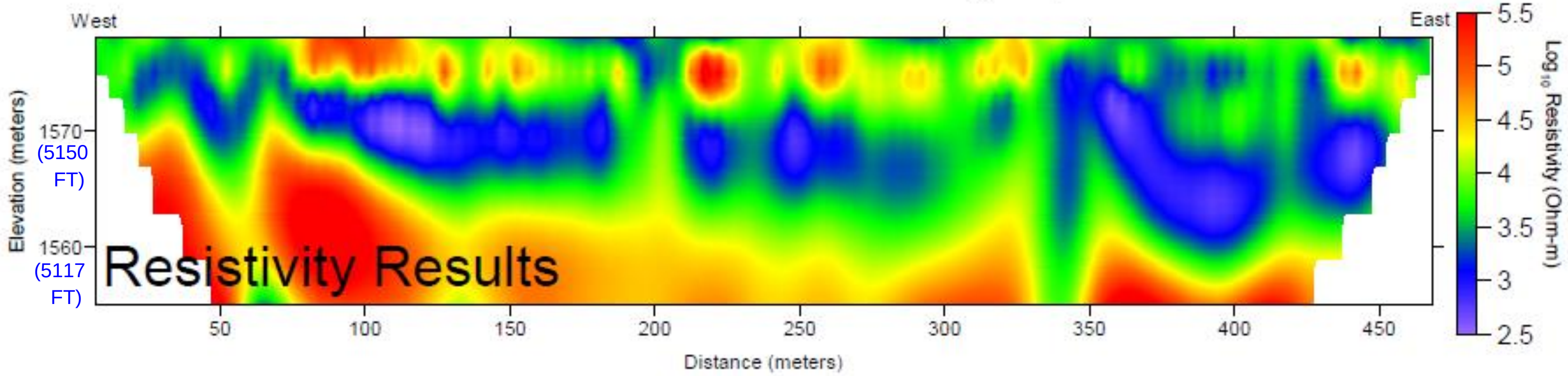
Provided by
Olson
Engineering

Olson ENGINEERING

Figure 12
Site A Electrical Resistivity
Tomography Results

LeonardRice
ENGINEERS, INC.
1221 Auraria Parkway | Denver, CO 80204
303-455-9589 | 800-453-9589 | Fax: 303-455-0115
www.LREwater.com

(Ground surface:
approximately 5224 FT AMSL)



DATE:
6/20/2017

Provided by
Olson
Engineering

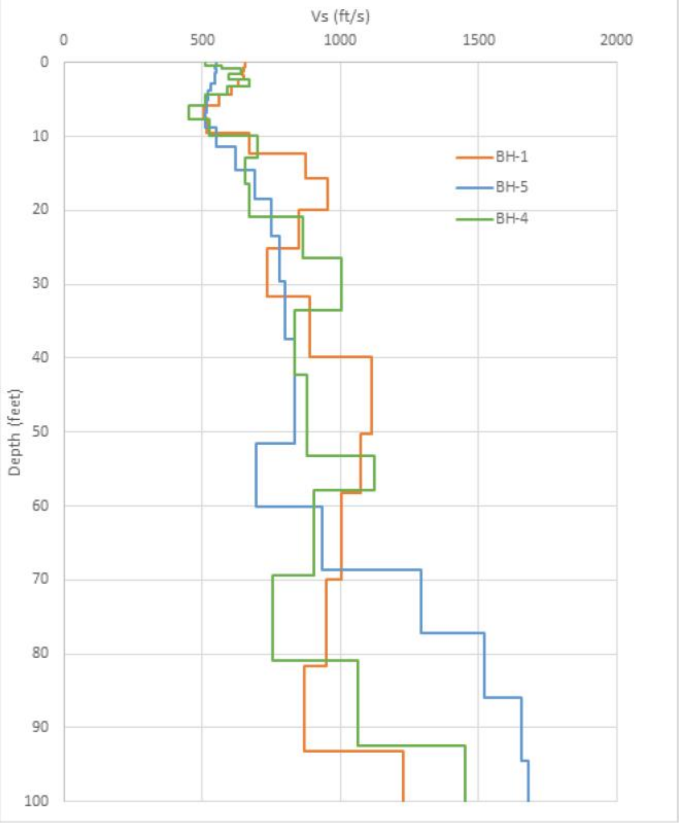
Figure 13
Site C Electrical Resistivity
Tomography Results

LeonardRice
ENGINEERS, INC.
1221 Auraria Parkway | Denver, CO 80204
303-455-9589 | 800-453-9589 | Fax: 303-455-0115
www.LREwater.com

Borehole 1			
Depth Range (feet)			Vs
0.0	-	0.3	655.4
0.3	-	0.7	656.9
0.7	-	1.1	650.3
1.1	-	1.7	644.9
1.7	-	2.4	652.0
2.4	-	3.3	633.4
3.3	-	4.4	604.2
4.4	-	5.7	561.9
5.7	-	7.5	509.0
7.5	-	9.6	516.2
9.6	-	12.3	672.7
12.3	-	15.7	873.6
15.7	-	19.9	952.8
19.9	-	25.1	848.4
25.1	-	31.7	735.4
31.7	-	39.9	890.4
39.9	-	50.2	1116.1
50.2	-	58.3	1071.7
58.3	-	69.9	1006.1
69.9	-	81.6	947.5
81.6	-	93.2	870.1
93.2	-	104.9	1227.7
104.9	-	116.5	1679.0
116.5	-	128.2	2054.6
128.2	-	139.8	2255.5
139.8	-	151.5	2275.2
151.5	-	163.1	2235.1
163.1	-	174.8	2014.8
174.8	-	186.4	1799.9
186.4	-	198.1	1576.9
198.1	-	209.8	1220.1
209.8	-	221.4	1080.8
221.4	-	276.8	2952.2

Borehole 4			
Depth Range (feet)			Vs
0.0	-	0.4	513.8
0.4	-	0.9	569.3
0.9	-	1.5	639.7
1.5	-	2.2	598.4
2.2	-	3.2	668.7
3.2	-	4.3	592.7
4.3	-	5.8	511.9
5.8	-	7.6	450.9
7.6	-	9.9	524.3
9.9	-	12.8	699.0
12.8	-	16.4	656.0
16.4	-	20.9	671.7
20.9	-	26.5	863.4
26.5	-	33.5	1003.2
33.5	-	42.3	834.2
42.3	-	53.2	879.3
53.2	-	57.8	1125.5
57.8	-	69.4	905.3
69.4	-	81.0	757.7
81.0	-	92.5	1066.4
92.5	-	104.1	1450.0
104.1	-	115.7	1706.9
115.7	-	127.2	1835.9
127.2	-	138.8	1833.8
138.8	-	150.3	1760.1
150.3	-	161.9	1665.2
161.9	-	173.5	1554.4
173.5	-	185.0	1468.1
185.0	-	196.6	1421.6
196.6	-	208.2	1407.1
208.2	-	219.7	1418.7
219.7	-	274.7	2327.3

Borehole 5			
Depth Range (feet)			Vs
0.0	-	0.3	549.9
0.3	-	0.8	547.9
0.8	-	1.3	553.9
1.3	-	2.0	546.2
2.0	-	2.8	547.1
2.8	-	3.8	532.7
3.8	-	5.1	522.3
5.1	-	6.8	514.4
6.8	-	8.8	509.3
8.8	-	11.3	550.6
11.3	-	14.5	621.4
14.5	-	18.4	692.1
18.4	-	23.4	750.4
23.4	-	29.6	779.4
29.6	-	37.3	801.7
37.3	-	51.5	835.4
51.5	-	60.1	697.1
60.1	-	68.7	935.4
68.7	-	77.3	1292.6
77.3	-	85.8	1519.3
85.8	-	94.4	1657.3
94.4	-	103.0	1683.0
103.0	-	111.6	1633.7
111.6	-	120.2	1549.1
120.2	-	128.8	1447.4
128.8	-	137.3	1341.2
137.3	-	145.9	1300.3
145.9	-	154.5	1246.8
154.5	-	163.1	1226.8
163.1	-	203.9	2089.4



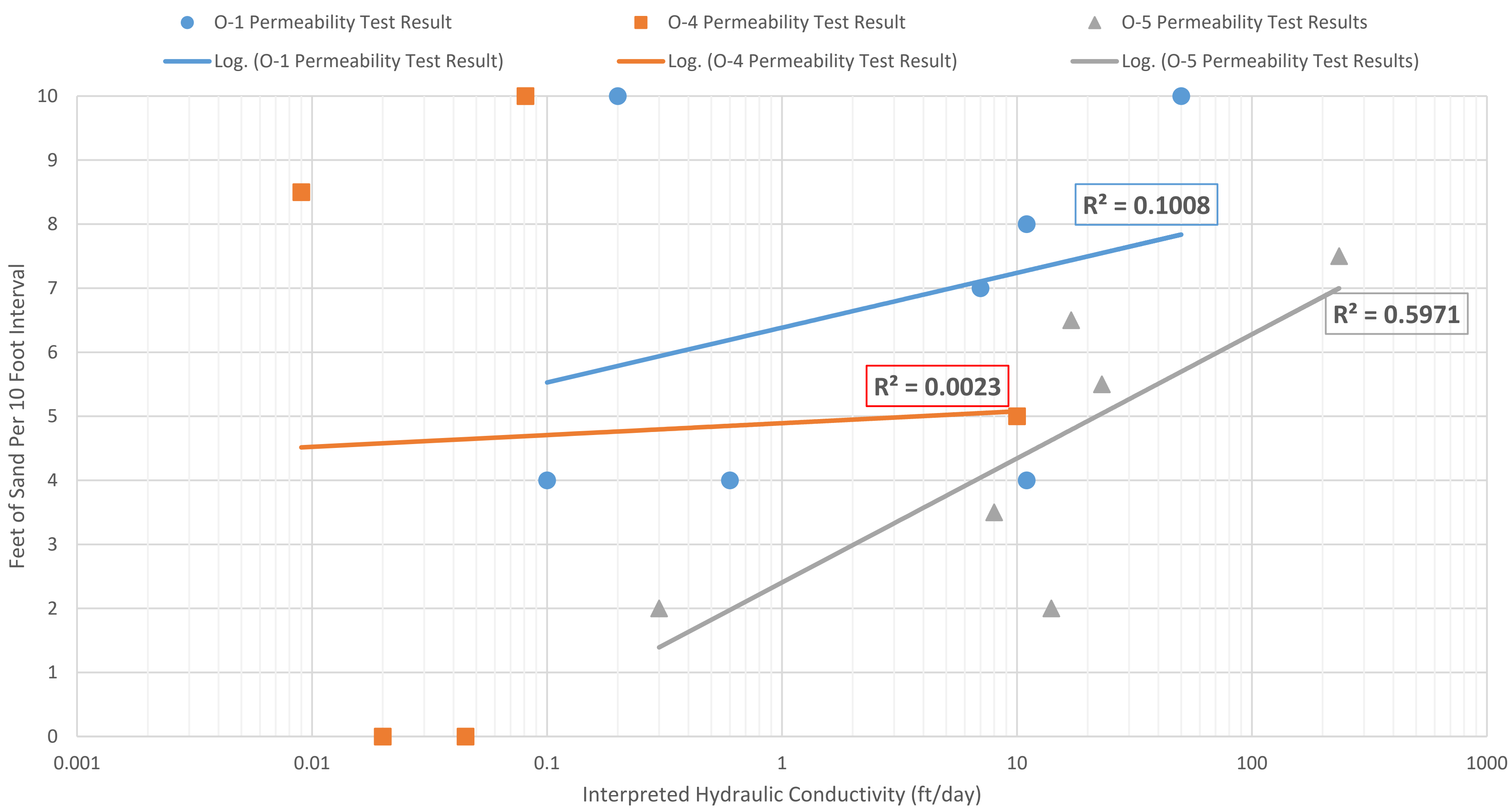
DATE:
6/20/2017

Provided by Olson Engineering

Olson ENGINEERING

Figure 14
Multi-channel Analysis of Surface Waves (MASW) Results

LeonardRice ENGINEERS, INC.
1221 Auraria Parkway | Denver, CO 80204
303-455-9589 | 800-453-9589 | Fax: 303-455-0115
www.LREwater.com



DATE: 6/20/2017

AUTHOR: Joel Barber

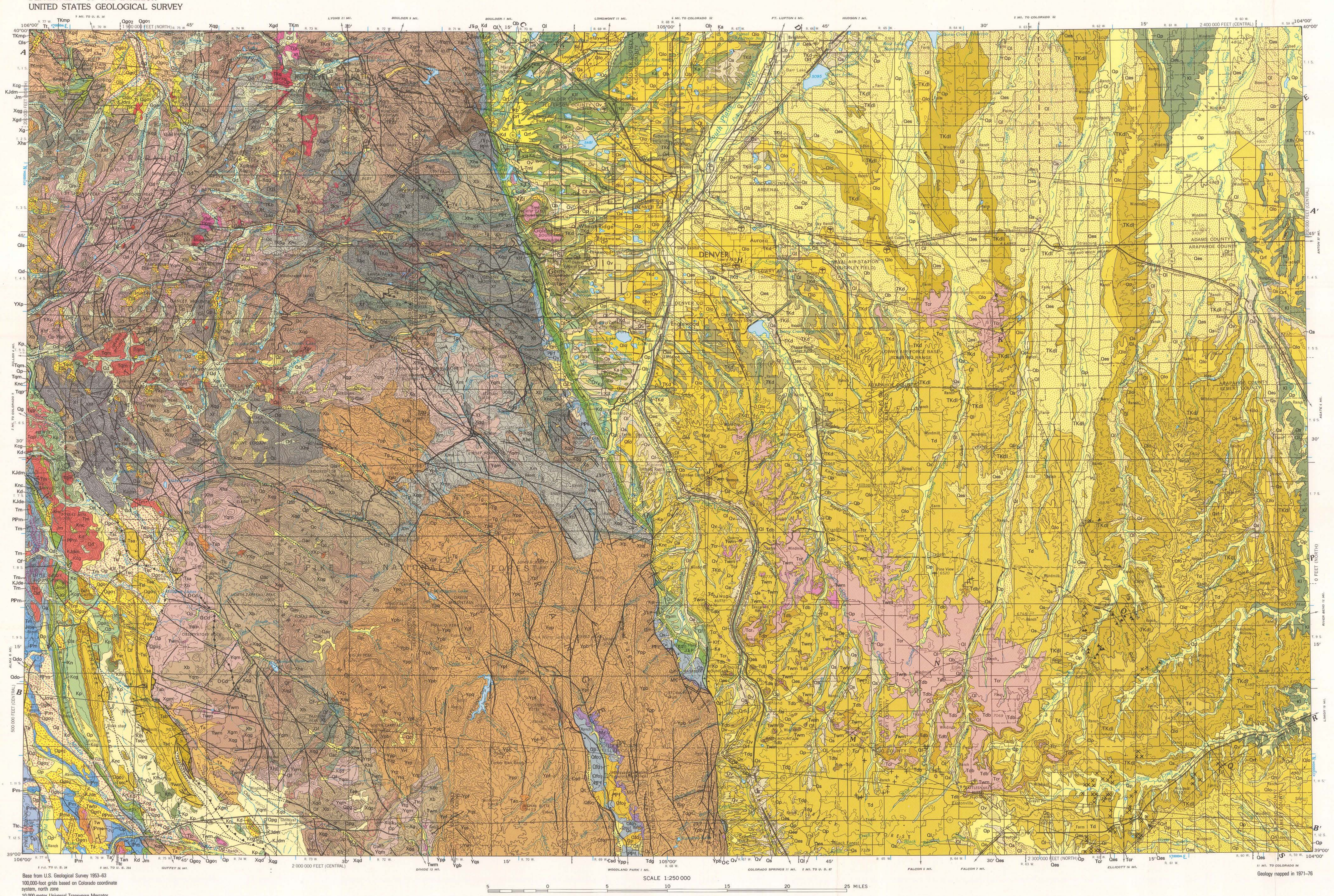
Figure 15
Permeability Test Results
Versus Feet of Observed Sand

LeonardRice ENGINEERS, INC.
1221 Auraria Parkway | Denver, CO 80204
303-455-9589 | 800-453-9589 | Fax: 303-455-0115
www.LREwater.com

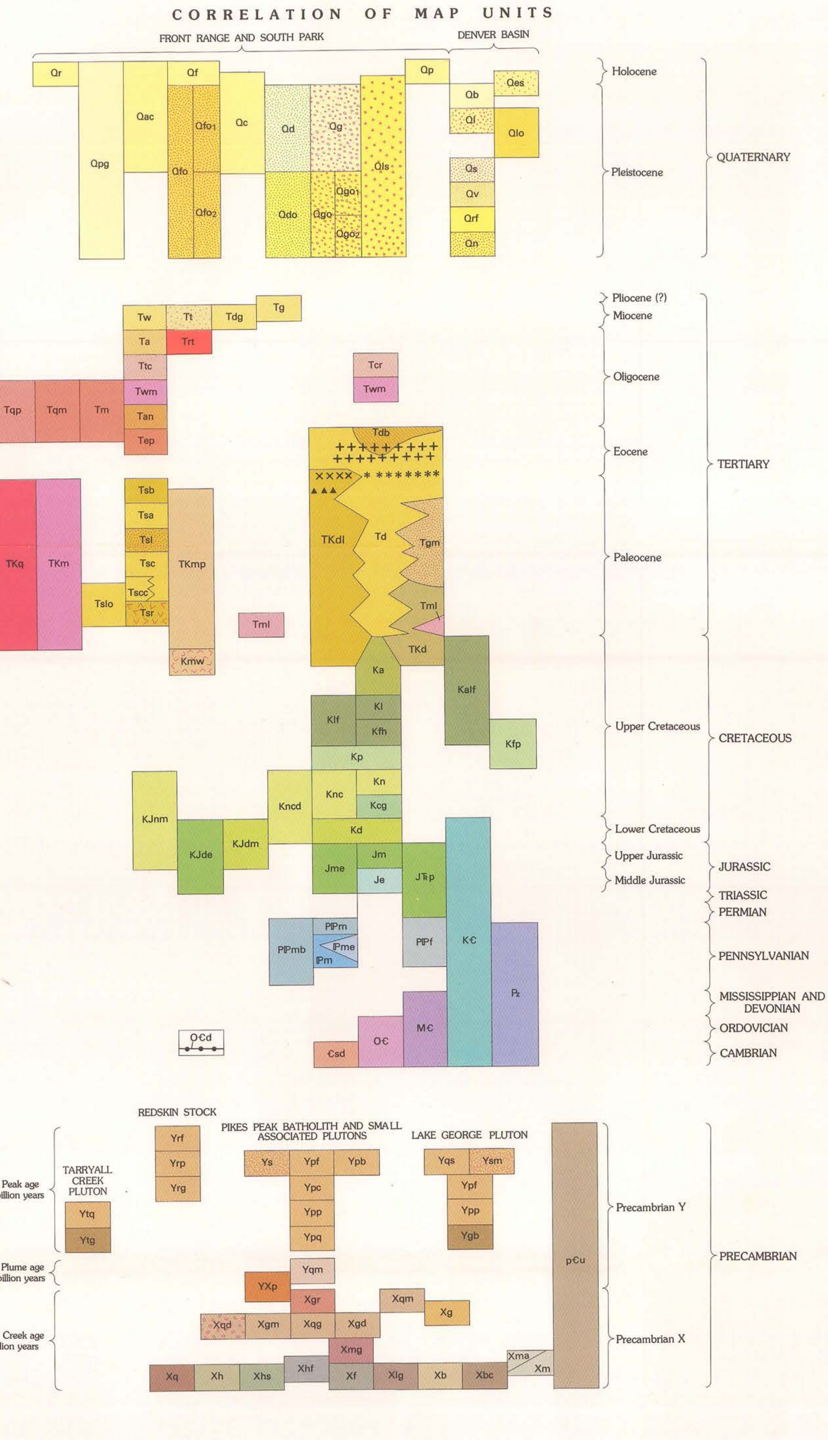
Appendix A – Lost Creek Basin Geology Map

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

MISCELLANEOUS INVESTIGATIONS SERIES
MAP I–1163 (SHEET 1 OF 2)



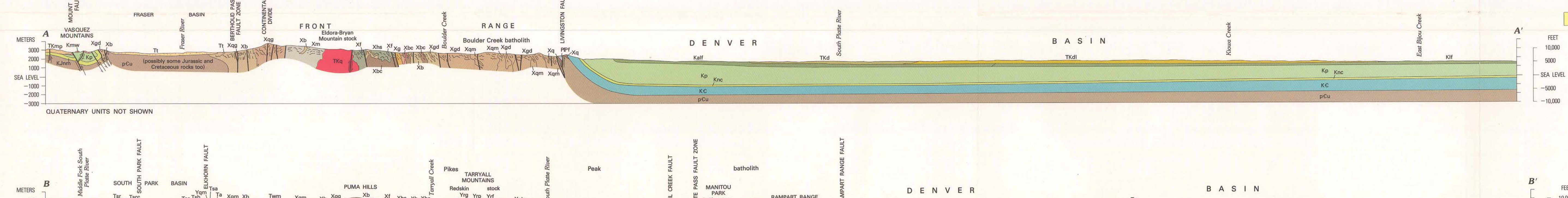
SCALE 1:250 000



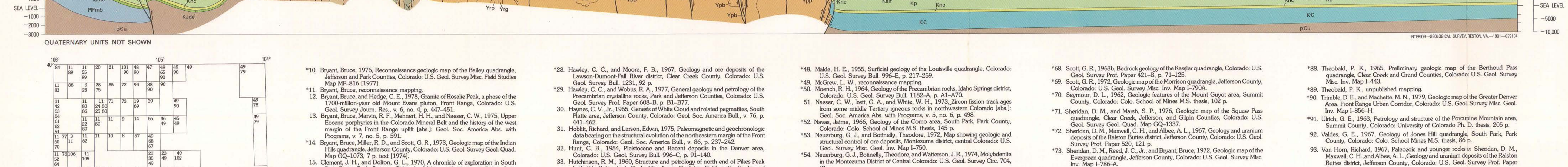
CORRELATION OF MAP UNITS

DESCRIPTION OF MAP UNITS

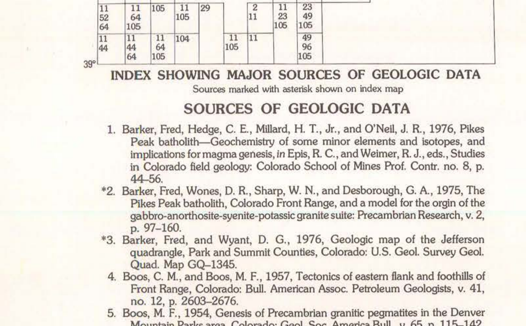
MISSISSIPPIAN, DEVONIAN, ORDOVICIAN, AND CAMBRIAN ROCKS
Leadville Limestone (Mississippian)—Gray, pink, and buff, fine- to coarse-grained limestone and dolomite. Present only in Manitou Park (T. 10–12 S., R. 69 W.) where maximum thickness is about 30 m
Williams Canyon Limestone (Devonian)—Lavender-mottled gray to buff, finely crystalline sandy dolomite or dolomitic limestone with thin interbeds of sandstone and shale. Present in Perry Park (T. 9–10 S., R. 68 W.) and Manitou Park (T. 10–12 S., R. 69 W.). Thickness about 14 m



QUATERNARY UNITS NOT SHOWN

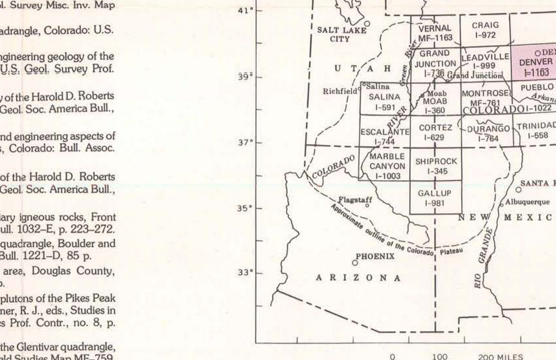


QUATERNARY UNITS NOT SHOWN

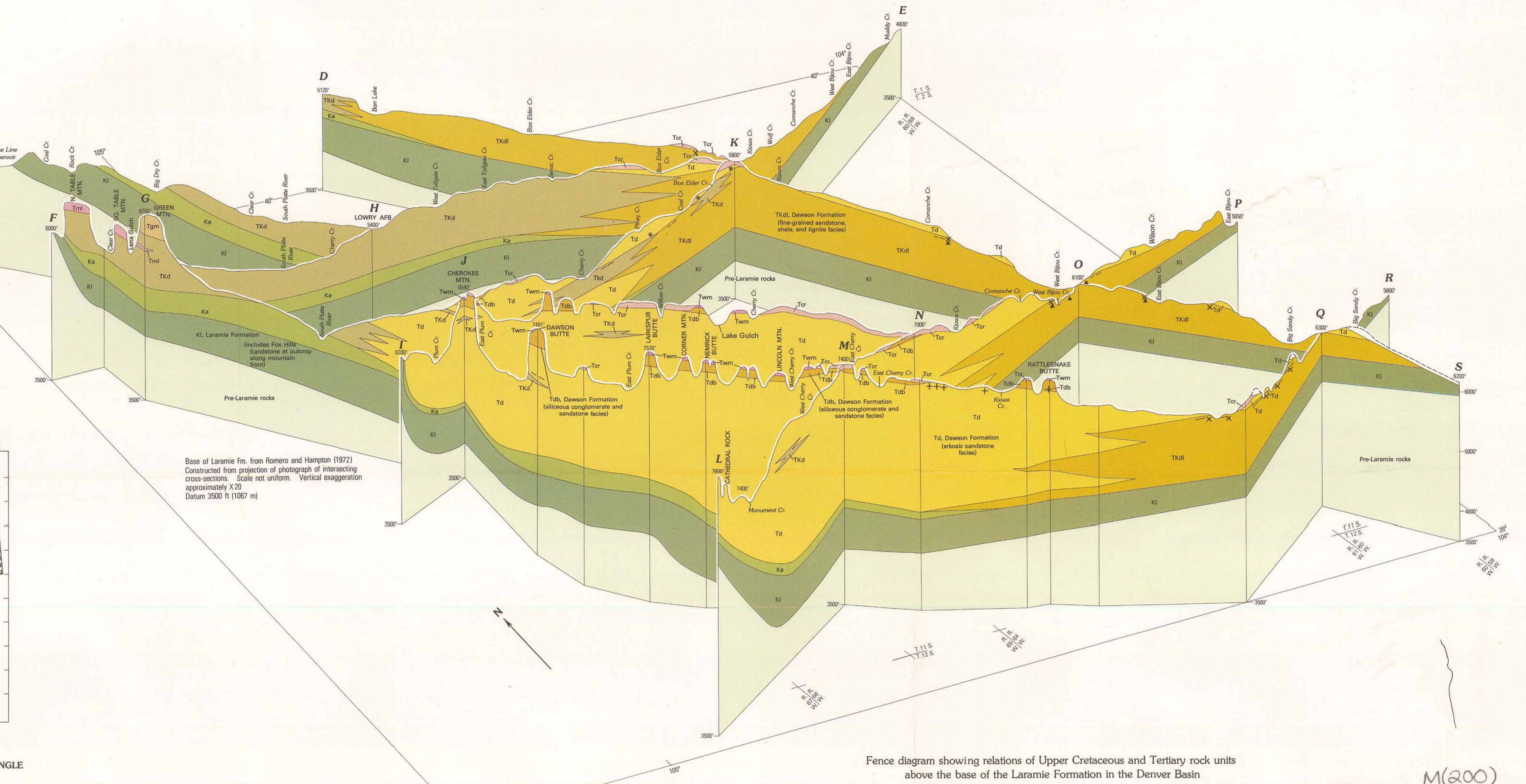


INDEX SHOWING MAJOR SOURCES OF GEOLOGIC DATA

SOURCES OF GEOLOGIC DATA



INDEX MAP SHOWING AREA OF DENVER 1° x 2° QUADRANGLE AND OTHER PUBLISHED 1° x 2° QUADRANGLE MAPS



Fence diagram showing relations of Upper Cretaceous and Tertiary rock units above the base of the Laramie Formation in the Denver Basin

Geology

GEOLOGIC MAP OF THE DENVER 1° X 2° QUADRANGLE, NORTH-CENTRAL COLORADO

By

Bruce Bryant, Laura W. McGrew, and Reinhard A. Wobus

1981

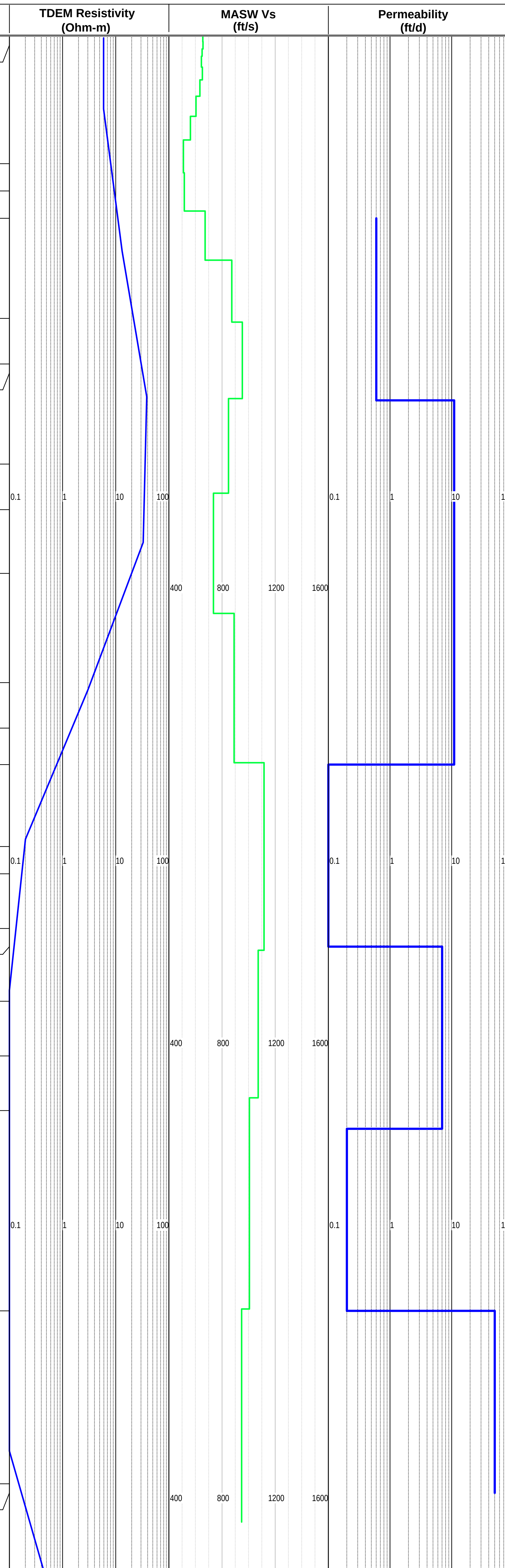
Appendix B – Test Hole Summary Logs

O-1
Total depth: 80
UTM Easting (ft):
UTM Northing (ft):
Elevation (ft):

Date drilled: 4/19/18
Permit number: N/A
Project number: 1412AUW02
Field Geologist: Joel Barber

LeonardRice
ENGINEERS, INC.
1221 Auraria Parkway | Denver, CO 80204
303-455-9589 | 800-453-9589 | Fax: 303-455-0115
www.LREwater.com

Depth (ft)	Lithology Log
0	CL: Clay
	SP: Poorly Graded Sand. Tan. Dry. Weak cohesion in sample.
	SP-SC: Poorly Graded Sand w/ Clay. Brown mottled with white. Dry. Calcite precipitate.
	SP: Poorly Graded Sand. Tan. Dry. Weak cohesion in sample.
-10	SC: Clayey Sand. Brown mottled w/ white. Cemented. Difficult drilling.
	SW: Well Graded Sand. Tan. Dry. Weakly cemented.
	SC: Clayey Sand. Brown mottled w/ white. Cemented. Difficult drilling.
-20	SW: Well Graded Sand. Tan. Dry. Weakly cemented.
	CL: Clay. Light brown. Dry. Calcite. Very stiff, apparent strong cementation.
	CL: Sandy Clay. Brown. Dry. Very weak cementation.
-30	SW: Well Graded Sand. Tan. Dry. Weakly to moderately cemented.
	SP: Poorly Graded Sand with Clay Beds. Tan. Dry. Weakly cemented.
	CL: Sandy Clay. Brown. Dry.
-40	SW-SC: Well Graded Sand w/ Clay. Brown. Moist. Moderate dry strength from cohesion or cementation.
	CL: Sandy Clay. Brown. Dry. Very high dry strength. Sonic rig cored through sample.
	SP: Poorly Graded Sand. Tan. Dry. Very weak cohesion/cementation.
-50	SP: Calcite rich Poorly graded Sand. White. Dry. Calcite "powder"
	SP: Poorly Graded Sand. Tan. Dry. Very weak cohesion/cementation.
	SW: Gravelly Well Graded Sand. Tan. Dry. No apparent cementation.
	CL: Sandy Clay. Brown. Dry. Very stiff/well cemented. Sample can't be broken by hand.
-60	SP: Poorly Graded Sand with Clay Laminations. Horizontal sructure - Laminated to thinly bedded. Weakly cemented.
-70	SP: Cemented Poorly Graded Sand with Clay Laminations. Horizontal sructure - Laminated to thinly bedded. Very well cemented.
-80	SW: Gravelly Well Graded Sand. Brown. Moist. No apparent cementation.



O-4

Total depth: 60

UTM Easting (ft):

UTM Northing (ft):

Elevation (ft):

Date drilled: 4/19/18

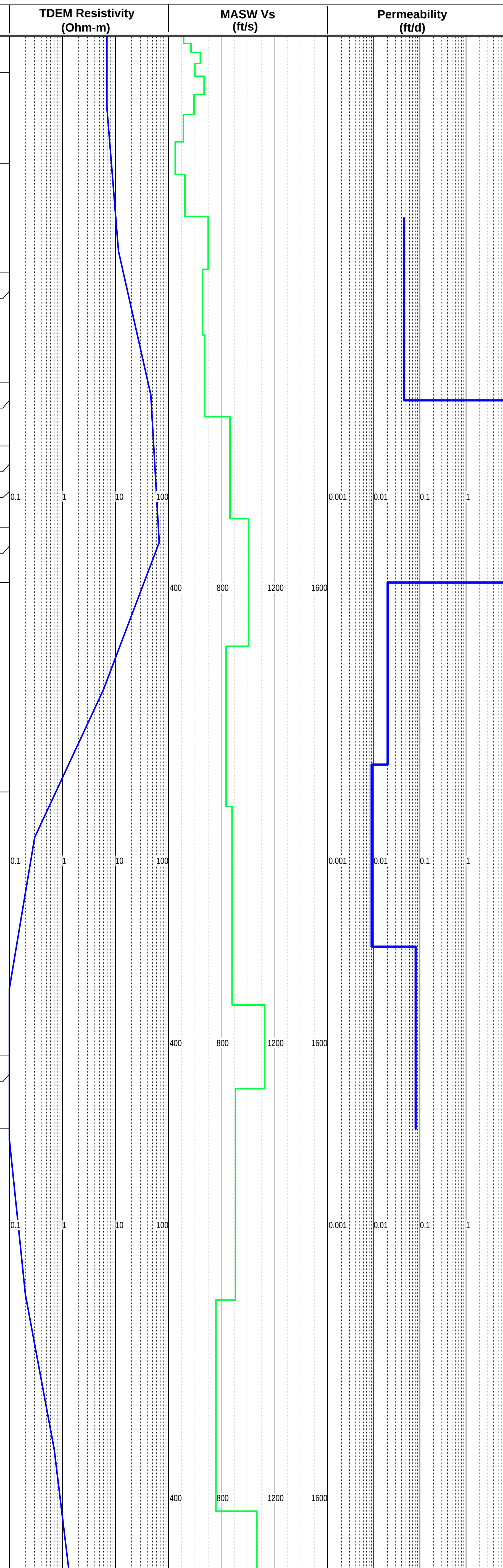
Permit number: N/A

Project number: 1412AUW02

Field Geologist: Joel Barber

LeonardRice ENGINEERS, INC.
1221 Auraria Parkway | Denver, CO 80204
303-455-9589 | 800-453-9589 | Fax: 303-455-0115
www.LREwater.com

Depth (ft)	Lithology Log
0	SC: Clayey Sand. Brown. Moist. Organics.
	SP-SC: Poorly Graded Sand s/ Some Clay. Light Brown. Dry.
	SC: Clayey Poorly Graded Sand. Light Brown. Dry. Weakly cemented, low dry strength.
-10	
	CL: Sandy Clay. Light brown. Dry. Strong dry strength/cementation. "Cored" by sonic rig.
	SC: Clayey Poorly Graded Sand. Light Brown. Dry. Weakly cemented, low dry strength.
	CL: Sandy Clay. Light brown w/ white staining. Dry. Strong dry strength/cementation. "Cored" by sonic rig.
-20	SP-SC: Poorly Graded Sand w/ Clay. Weak cementation/dry strength.
	SW: Gravelly Well Graded Sand. Tan. Dry. No apparent cementation.
	SW-SC: Well Graded Sand w/ Clay. Brown. Dry. Moderately Cemented.
	SW: Gravelly Well Graded Sand. Tan. Dry. Well cemented.
	SW-SC: Well Graded Sand w/ Clay. Brown. Dry. Moderately Cemented.
	SW: Gravelly Well Graded Sand. Tan. Dry. No apparent cementation.
-30	CL-SC-SP: Interbeded CL, SC, SP-SC, and SP. Brown. Dry. Well cemented with moderate to high dry strength. Predominately sand with thin clay beds. Horizontal bedding structure.
-40	
	SW: Well Graded Sand. Tan. Dry. Well cemented with a weak horizontal structure. Contains infreqent very thin to thin clay beds.
-50	
	SW: Well Graded Sand. White. Dry. Calcite cement broken up into powder by sonic rig.
	SW: Well Graded Sand. Tan. Dry. Very well cemented, appears as sandstone with calcite cement.
-60	
-70	
-80	

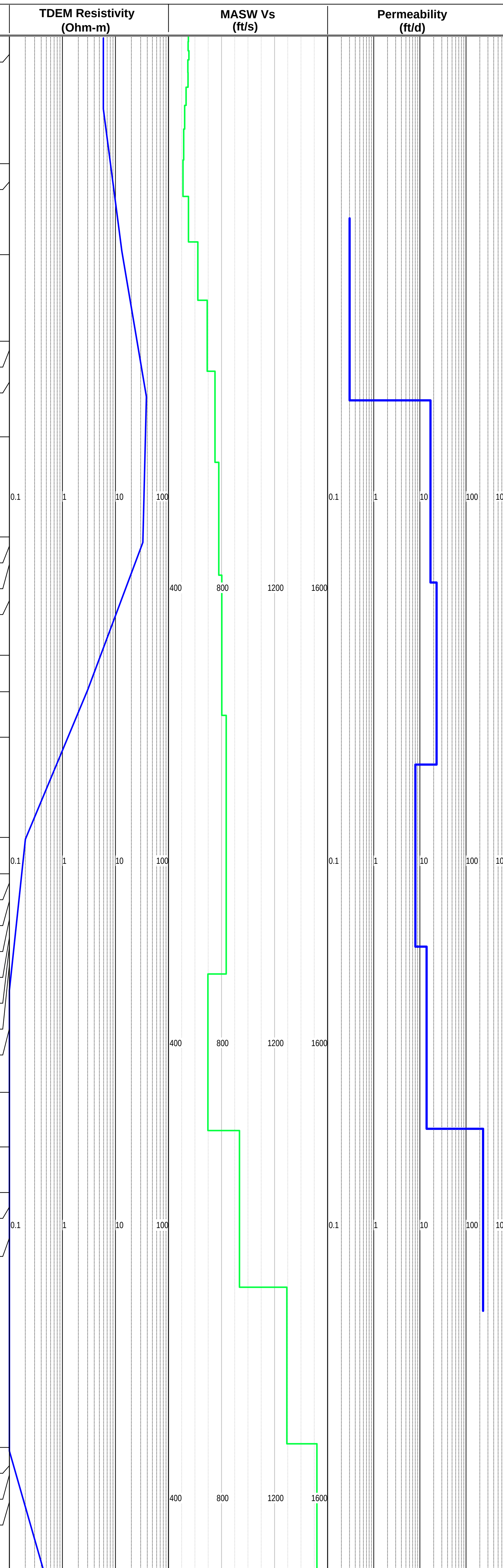


O-5
Total depth: 85
UTM Easting (ft):
UTM Northing (ft):
Elevation (ft):

Date drilled: 4/23 to 4/24/18
Permit number: N/A
Project number: 1412AUW02
Field Geologist: Joel Barber

LeonardRice ENGINEERS, INC.
1221 Auraria Parkway | Denver, CO 80204
303-455-9589 | 800-453-9589 | Fax: 303-455-0115
www.LREwater.com

Depth (ft)	Lithology Log
0	SC: Clayey Poorly Graded Sand with Organics. Dark Brown. Moist. Contains frequent roots.
	SC: Clayey Poorly Graded Sand. Brown. Moist. Some white (calcite) staining.
	CL: Sandy Clay. Dark brown. Moist.
-10	SC: Clayey Poorly Graded Sand. Brown. Moist. Some white (calcite) staining.
	SP-SC: Poorly Graded Sand w/ Clay.
	CL: Sandy Clay. Brown. Moist.
	SW: Well Graded Sand w/ Some Gravel. Tan. Moist.
-20	SC: Clayey Sand. Brown to tan. Moist.
	SP: Poorly Graded Sand. Tan. Moist.
	SC: Clayey Poorly Graded Sand. Tan. Moist to wet.
-30	SP: Poorly Graded Sand. Tan. Moist.
	SC: Clayey Sand. Light brown to brown. Very weak cohesion/potential cementation. Weak horizontal thin bedding.
	SP: Poorly Graded Sand. Tan. Moist.
	SP-SC: Poorly Graded Sand w/ Clay. Tan. Moist. Weakly cemented. Horizontal thin bedding structure.
	SW: Gravelly Well Graded Sand. Light brown and mottled. Moist. Very weakly cemented.
-40	SP-SC: Poorly Graded Sand w/ Clay. Tan. Moist. Weakly cemented. Horizontal thin bedding structure.
	SP: Poorly Graded Sand. White. Dry. Broken up calcite powder in sample.
	SP-SC: Poorly Graded Sand w/ Clay. Tan. Moist. Weakly cemented. Horizontal thin bedding structure.
	SP: Poorly Graded Sand. Light brown. Moist.
-50	SW: Well Graded Sand. Light brown. Moist.
	SP-SC: Poorly Graded Sand w/ Clay. Tan. Moist. Weakly cemented. Horizontal thin bedding structure.
	SW: Well Graded Sand. Light brown. Moist.
	CL: Clay w/ Sand. Brown. Moist. Sonic barel "cored" throug clay.
	SC: Well Graded sand w/ Clay. Tan mottled with dark brown. Moist.
	SP-SC: Poorly Graded Sand w/ Clay. Tan. Moist. Weakly cemented. Horizontal thin bedding structure.
-60	SP: Poorly Graded Sand. Tan. Dry. Weakly cemented.
	SW: Interbedded Well Graded Sand with varying colors from black to tan to brown. Moist.
	SC: Clayey poorly graded sand. Light brown. Moist.
	SC-SW-SP: Interbedded SP and SW. Dry. Tan to light brown mottled with white. Moderately to well cemented. Calcite staining.
-70	SW: Well Graded Sand. Brown. Moist to wet.
	CL: Clay. Grey. Wet.
-80	SC: Clayey Sand. Tan. Wet.
	SW: Well Graded Sand. Brown. Moist to wet.
	Denver: Denver Formation. Blue shale and very fine grained sandstone.



O-5
Total depth: 85
UTM Easting (ft): -104.517251
UTM Northing (ft): 39.880174
Elevation (ft): 5246

Date drilled: 4/23 to 4/24/18
Permit number: N/A
Project number: 1412AUW02
Field Geologist: Joel Barber

LeonardRice
ENGINEERS, INC.
1221 Auraria Parkway | Denver, CO 80204
303-455-9589 | 800-453-9589 | Fax: 303-455-0115
www.LREwater.com