Phase III Hydrogeologic Study of the Mamm Creek Area
Garfield County, Colorado

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Table of Contents

FIGURES

TABLES

APPENDICES

EXECUTIVE SUMMARY

The objective of the Phase III Hydrogeologic Characterization for the Mamm Creek Study Area was to gather additional data to clarify the nature of the hydrologic flow system and water quality in the study area, including evaluating the possible effects, if any, of oil and gas development on the Wasatch Formation water quality. The Study Area was also evaluated as part of the Phase I hydrogeologic study for the Mamm Creek Field Area (URS, 2006) and the Phase II hydrogeologic study (S.S. Papadopulos, 2008). The Study Area is located south of the Colorado River between the cities of Rifle and Silt, Colorado (Figure 1), and is approximately 110 square miles in size and comprises the majority of the Mamm Creek gas field in the southeastern portion of the Piceance Basin. This study is an attempt to improve understanding of the nature of groundwater chemistry in the vicinity of the installed monitoring wells, including better understanding of groundwater chemistry in the hydrogeologic layers located about 200 feet deeper than those typically utilized for domestic purposes.

The Phase III Hydrogeologic Characterization activities included the drilling and installation of three pairs of shallow (~400 feet) and deep (~600 feet) monitoring wells to enhance Garfield County's monitoring capabilities in the Mamm Creek area. The investigation also included conducting four water quality sampling events for each installed well, as well as from a nearby residential well. The monitoring wells were intended to allow data collection to evaluate the vertical hydraulic gradients and water quality in the study area, including evaluating the effects, if any, of oil and gas development on the Wasatch Formation at the locations of the nested monitoring wells.

This report is comprised of eight sections which describe the efforts associated with the hydrogeologic characterization in the context of past investigations, and includes:

1. Introduction
2. Study Area Description
3. Methodology and Well Installation
4. Phase III Data Summary
5. Data Interpretation
6. Discussion
7. Summary of Findings
8. Recommendations

The area in the immediate vicinity of the investigation wells includes the Mamm Creek Special Drilling Zone, an area characterized by its alignment with the axis of a plunging anticlinal structure, and the related high-angle fracturing present as a result. Natural gas formed thousands of feet deep below land surface and pressurized fluids may have been continuously escaping to the surface over time through these fractures, causing localized impacts to groundwater. This study has attempted to answer questions about the nature of the groundwater chemistry in the vicinity of the wells as well as contributing to the understanding of groundwater chemistry in the hydrogeologic layers present 200 feet deeper than those typically pumped for domestic purposes.

Limited water production from the monitoring wells prevented the removal of the planned 5 casing volumes during well development. The lack of water production and inability to fully develop the wells was a result of the low formation permeability and the fact that small screen intervals were used to collect samples from discrete depth intervals. During the initial two groundwater sampling events, several water quality parameters including pH, alkalinity, and TDS were observed to vary from the anticipated range. It appeared that cement-grout used during well construction may have been impacting the chemistry of the nested-well groundwater quality as a result of grout or high-pH, high alkalinity water from grouting activities seeping into fractures in the surrounding formation, and the inability to completely remove these materials during initial well development due to the lack of water production. Two redevelopment events were conducted, resulting in decreased pH values in MW-2A and decreased field-measured conductivity values in all wells that suggest redevelopment activities were partially successfully at removing some of the cement-grout in the surrounding fracture network. Although the cement-grout used during well construction may be affecting groundwater chemistry in terms of elevated pH, the impacts of the cement-grout are expected to dissipate with time. In addition, the observed dissolved gas concentrations are believed to be representative, and the various chemical parameters monitored as part of this investigation are believed to be representative of local groundwater chemistry.

The Phase III Hydrogeologic Characterization found that the water quality of the samples collected from the investigation wells was generally saline, alkaline and high TDS, and contained dissolved methane concentrations ranging from less than 1 mg/L (MW-3B) to 140 mg/L (MW-2A).

Groundwater chemistry in samples collected from the Phase III wells generally reflects higher sodium and chloride concentrations than would be expected in shallow water-table wells which are primarily influenced by surface recharge. Elevated sodium, chloride, and TDS, particularly in MW-1B, MW-2A, and MW-3A suggest the possibility of external sources of these solutes. These may include localized dissolution of naturally occurring minerals, seasonal influences related to snowmelt and stream chemistry, or vertical migration of groundwater from deeper bedrock depth intervals. Benzene was found as a concentration above the EPA National Primary Drinking Water Regulations Maximum Contaminant Level (MCL) standard (5 µg/L) in MW-1B in the January 2011 water sample (5.3 µg/L). The remaining samples from MW-1B and the other Phase III monitoring wells did not contain benzene above the MCL. The source of benzene in MW-1B is unknown.

Dissolved methane concentrations of greater than 1 mg/L, were found in all of the Phase III wells. Of these wells, MW-3B and the Currie Well contained less than 10 mg/L and the remaining wells had at least one sample with a result that was greater than 10 mg/L. The highest reported concentration in MW-3B and the Currie Well were 2.3 mg/L and 5.6 mg/L, respectively. In Well Nest 1 (MW-1A, MW-1B), methane concentrations were higher in the deeper well (MW-1B) during the January 2011 and May 2011 sampling events. However concentrations in MW-1B declined after the May 2011 sampling event and concentrations were higher in the shallow wells during the August 2012 and December 2012 sampling events. In both Well Nest 2 and Well Nest 3, methane concentrations were higher in the shallow well than the deeper well.

Carbon and hydrogen isotopic analysis of dissolved methane suggest a thermogenic source in MW-1B, and MW-2B. Biogenic methane derived from reduction of carbon dioxide (CO_2) is more likely in MW-2A, MW-3A, and the Currie Well. The source(s) of methane in MW-1A and MW-3B are unclear. The results from MW-1A may possibly represent either a biogenic source, a mix of biogenic and thermogenic sources, or an intermediate step in isotopic fractionation between the two zones on the isotopic diagrams. Isotopic analysis of the sample collected from MW-3B during the January 2011 event appears to represent a thermogenic source; however, the corresponding isotopic analysis from the May 2011, August 2012, and December 2012 events may represent either a mix of biogenic and thermogenic sources, or an intermediate step in isotopic fractionation between the two zones on the isotopic diagrams.

Wet-gas ($C_2 – C_4$) analyses suggest that the methane present in MW-1B and MW-2B is thermogenic. Chemical composition of water samples collected from MW-1A and MW-3B contain wet-gas chemistry that implies possible mixing contributions of thermogenic gas. Low concentrations of wet-gas components were detected in all samples collected from some of the events. The concentration percentages were low (typically less than 0.1 percent). The source of these components is unclear. Analysis of the samples collected from the Currie well suggests a biogenic source, lacking significant concentrations of wet-gas constituents.

Generally speaking, the dissolved methane observed in shallow wells (<400 feet deep) in the study area appears to have a biogenic source. This is consistent with observations from each of the three sets of nested wells in which shallow nested wells MW-1A, MW-2A and MW-3A, as well as the Currie well, all appear to be either biogenic carbonate-reduction in source, or mixed biogenic-thermogenic in the case of MW-1A. The dissolved methane observed in the deeper of wells in the nested pairs appears to be thermogenic in origin based on carbon and hydrocarbon isotopic analysis. Thermogenic methane concentrations observed in deeper wells have generally been constant or declining between 2011 and 2012. In samples collected in 2012, the highest observed concentration of dissolved thermogenic methane was 8.7 mg/L in MW-1B and the lowest concentration was 0.53 mg/L in MW-3B.

Bacteria (acetogenic, fermenting, and methanogenic) necessary to perform the carbonate-reduction reactions necessary to generate biogenic methane may be present in the upper 400 feet of the low-permeability siltstones around the nested wells, but are either not present at greater depth, or one of the other requirements of the reaction pathway (such as the availability of acetate) is not present. Groundwater present in the wells screened in the upper 400 feet generally is characterized by reducing conditions (low dissolved oxygen, low redox measurements, hydrogen sulfide odor). Since oxidation of thermogenic methane to CO_2 would lead to additional fractionation and shift the isotopic composition of the remaining methane further into the thermogenic zone, it seems unlikely that the thermogenic methane observed deeper is the source material from which the shallow biogenic methane is derived.

1.0 INTRODUCTION

1.1 Objectives

The objective of the Phase III Hydrogeologic Characterization for the Mamm Creek Study Area was to gather additional data to clarify the nature of the hydrologic flow system and water quality in the study area, including evaluating the possible effects, if any, of oil and gas development on the Wasatch Formation water quality. Nested groundwater monitoring wells were installed to facilitate collection of data for the evaluation of three-dimensional hydrologic flow system and water quality in the Mamm Creek study area to assist in achieving these objectives. Data obtained during this investigation was also used to further evaluate the results of the Phase I and Phase II hydrogeologic studies performed in this area.

1.2 Project Approach

To achieve project objectives, previously generated data associated with the Phase I and Phase II hydrogeologic studies were evaluated to provide guidance on selecting appropriate drilling locations. The locations were based on geologic structure, proximity to natural gas production areas, accessibility, and the ability of Garfield County to negotiate access agreements for well installation.

The well designs and installations were intended to maximize the cost-efficient collection of relevant data by nesting two wells, each completed in vertically discreet geologic strata and at different depths, in one boring. This design allowed evaluation of the vertical flow field within the groundwater system and resulting variations in water quality.

Groundwater levels and water quality samples were collected from each of the six wells installed in three well nests. In addition, a domestic well (Currie Well) was included for water-level monitoring and water quality sampling. Based on the relative water levels and completion intervals in each of the wells, three dimensional flow patterns were interpreted. Data from groundwater sample analyses were evaluated with respect to water type and origin. Water quality analyses were conducted for a list of organic and inorganic parameters, as well as for various dissolved gases including the stable carbon and hydrogen isotopes of methane. A list of the parameters is presented in section 3.8.

2.0 STUDY AREA DESCRIPTION

2.1 Study Area Location

The study area is located in northwest Colorado in southern Garfield County, south of I-70 and the Colorado River, between and south of the cities of Rifle and Silt (Figure 1). The study area extends approximately 9½ miles south of the Colorado River and covers an area of approximately 110 square miles.

2.2 Study Area Description

The primary land use is rangeland and ranching (residential) with limited commercial use. Oil and gas development is active in parts of the study area. Within the study area, the ground surface ranges from an elevation of 9,400 feet above mean sea level (ft amsl) in the southwest corner above West Mamm Creek, to a low of 5,280 ft amsl along the Colorado River in the northwest corner near the town of Rifle.

The study area includes (listed from west to east) the eastern portion of Taughenbaugh Mesa and all of Flatiron Mesa, Grass Mesa, and Hunter Mesa. Battlement Mesa and Grand Mesa are the highest terrain in the area but are both located outside the study area to the southwest. Annual precipitation generally increases toward the south of the study area and ranges from a low of 12.75 inches at low elevations (along the Colorado River valley) to almost 30 inches per year in the higher elevations on the flanks of Battlement Mesa (URS, 2006). The area experiences regular winter snowfall and snow accumulation on local roads. Most roads in the study area are unpaved, although some are asphalt surfaced, to minimize erosion and provide better surfaces for vehicular traffic during wet conditions and winter months.

The Mamm Creek Study Area includes more than 500 known and permitted domestic and livestock water supply wells in the area. A detailed description of the geographic setting, overall land use, and development of natural gas resources in the area is reported in the Phase I Hydrogeologic Study (URS, 2006).

The Colorado Oil and Gas Conservation Commission (COGCC) Mamm Creek Field Special Drilling Zone exists within the study area boundaries. This area was the subject of a Notice to Operators as of July 23, 2004 (revised February 9, 2007) that established special drilling and completion procedures due to repeated reports of problems drilling and completing wells including lost circulation and pressure bumps during drilling, loss of cement during completion activities, and persistently elevated bradenhead pressures (COGCC, 2004). The Mamm Creek Field Special Drilling Zone coincides geographically with the structural axis of the Divide Creek anticline, a local upwarping of the stratigraphy associated with deep fault-driven structural-block uplift caused by a series of northwest-southeast oriented thrust faults. The location of the Mamm Creek Field Special Drilling Zone is provided on Figure 2. The locations from which samples were collected as part of this study are also displayed on Figure 2.

2.3 Previous Studies

Previous investigations into the hydrogeology and water quality in the study area include a March 2006 Phase I Hydrogeologic Characterization of the area conducted by URS Corporation (URS, 2006). The stated objective of this study was to conduct a comprehensive investigation of the groundwater and surface water resources in the Mamm Creek area to provide an analysis of their vulnerability to impact from natural gas exploration and other human activities. The Phase I characterization involved the compilation and evaluation of existing groundwater data collected from wells in the vicinity and north of the Mamm Creek area. The characterization study described the geology and groundwater quality of the area using the results of approximately 3,000 individual samples. This characterization included inorganic compound analysis focusing on concentrations of dissolved species such as chloride, sodium, and sulfate. It also began a process documenting the locations in which dissolved methane was found in shallow groundwater wells and to evaluate the source(s) of that methane from an isotopic perspective. Methane was not detected in most of the water samples collected from the western portion of the study area, but was detected at elevated concentrations in the eastern portion of the study area.

As a direct follow-up to the Phase I characterization, in September 2008, S.S. Papadopulos & Associates, Inc. conducted a Phase II Hydrogeologic Characterization of the area (S.S. Papadopulos, 2008). The emphasis of the study was on collection of additional water quality, gas composition, stable carbon, and hydrogen isotopes of dissolved methane data from both domestic water supply wells and natural gas wells. Samples were collected from 66 domestic water supply wells and included analysis for a suite of inorganic parameters. In addition, water samples from 13 wells were analyzed for dissolved methane, with gas composition and hydrogen and carbon stable isotopes of methane analysis in 11 of these wells. In a separate sampling event, produced water samples were collected from 16 active natural gas wells and production gas samples were collected from four wells. The produced water samples were analyzed for inorganic parameters and the gas samples were analyzed for gas composition and hydrogen and carbon-stable isotopes of methane.

The Phase II Characterization study found that the distribution of water types indicated by the inorganic chemistry suggested the possibility that water from depth may be mixing with the Wasatch aquifer. Areas with elevated sodium-chloride concentrations may be experiencing mixing with water sourced in the Williams Fork Formation, from which natural gas is currently being produced. It also found that while most of the domestic wells had hydrocarbon gas characteristics consistent with a biogenic source, two of the wells sampled indicated a possible thermogenic source.

A review of Phase II hydrogeologic study was undertaken in 2008 by Dr. Geoffrey Thyne of Science Based Solutions, LLC (Thyne, 2008). This study used previously generated data to describe the nature of the geochemical conditions of the study area. Indications of the hydraulic relationship between the Wasatch and the underlying Mesaverde Group, the orientation and extent of fractures and structural features, any potential influences on water chemistry from natural gas wells or gas development activities such as hydraulic formation fracturing and well construction, and other anthropomorphic activities such as land cultivation, were considered in this evaluation. Dr. Thyne's summary of the Phase I and II hydrogeologic investigation data included several conclusions. These include that the water quality data collected in the two investigations was sufficient to establish a range for naturally occurring background chemistry, and impacts from petroleum activity were not at levels above regulatory standards. He concluded that there was a temporal trend of increasing methane concentrations in groundwater samples during the seven-year period for which the data had been collected, and that other than those samples collected in stream bottoms, the samples with elevated methane represented a probable thermogenic origin. The report also identified increases in chloride concentrations in groundwater which Dr. Thyne concluded were likely associated with produced water.

In 2009, the United States Geological Survey (USGS) published a report evaluating sources and sinks of nitrate and methane in groundwater from the Wasatch Formation in Garfield County (McMahon, et al, 2009). Data were evaluated by the use of concentrations of major ions, nutrients, oxidation-reduction (redox) constituents, noble gases, hydrocarbon molecular and isotopic compositions, water isotopic compositions, and tracers of groundwater age. Samples were collected from 26 domestic wells, 16 of which were located to the south of the Colorado River in the Mamm Creek Study area. The USGS study concluded that the sources of elevated-concentration methane (> 1 mg/L) in the Wasatch Formation were biogenic in origin in some places, even when sourced at significant depth, and thermogenic in others, when associated with the Mesaverde group. The primary sink of methane in the Wasatch Formation was shallow oxidation on the basis of dissolved oxygen and methane isotope data.

3.0 METHODOLOGY AND WELL INSTALLATION

3.1 Well Locations

Within practical constraints (including physical access and property rights), the well nest locations were selected to optimize data collection to meet the stated project objectives. Three well nest locations are shown on Figure 2 through 4. Figure 2 illustrates the location of the selected well nest locations relative to the Mamm Creek Field Special Drilling Zone. Figure 3a shows the well locations relative to those of other wells in the vicinity observed in past studies to contain dissolved methane. Figure 3b shows the well nest locations relative to gas wells in the vicinity based on information available from the COGCC. Figure 4 depicts the mapped structures and associated lineations present in the Mamm Creek area relative to the selected locations for the wells.

Final locations were selected based on the ability of Garfield County to obtain landowner permission. Each of the well nests was designed to include a shallow well, designated the "A" well, and a deep well, designated the "B" well (e.g. MW-1A and MW-1B). The shallow well was intended to be screened in the interval associated with the deeper of the residential wells in the vicinity, and the deeper well was intended to be screened slightly deeper than the domestic wells in the area. The Phase I report identifies that the deepest domestic well in the study area is 600 feet deep.

To identify these locations, Tetra Tech researched publicly available maps and databases for topography, gas wells, water wells, hydrogeology, and geology in the study area, including data from the URS Phase I and the S.S. Papadopulos Phase II reports. This information was extracted and digitized and the resulting data were formatted for use in ArcGIS, a geographic information system (GIS) program. Data from each of these sources was processed and filtered to match drilling objective criteria such as filling data gaps in areas with elevated thermogenic methane, elevated joint-set density, and geologic structures such as anticlines. Each of these data sources was layered using the GIS to identify the best location to site the well nest.

Based on this information, the proposed well location information was provided to Garfield County who worked with individual landowners to obtain access agreements at or near the recommended well locations.

Wells were installed at locations intended to be representative of groundwater conditions across the study area; however, since the study area encompasses a diverse mixture of geologic and geomorphic terrain with wide ranges in elevation, investigative results from wells installed as part of this study may not be representative of conditions that may be observed at all locations across the study area.

The borehole and nested wells for Well Nest #1 (MW-1A and MW-1B), were drilled and installed in the SE ¼, SW ¼ of Section 1 in Township 7 South, Range 92 West at a land surface elevation of 6,070.4 ft amsl. The borehole and nested wells for Well Nest #2 (MW-2A and MW-2B), were drilled and installed in the NW ¼, NE ¼ of Section 35 in Township 6 South, Range 92 West at a land surface elevation of 6,000.3 ft amsl. The borehole and nested wells for Well Nest #3 (MW-3A and MW-3B), were drilled and installed in the NW ¼, SE ¼ of Section 12 in Township 7 South, Range 92 West at a land surface elevation of 6,166.8 ft amsl.

3.2 Drilling and Lithologies Encountered

Prior to drilling, the Utility Notification Center of Colorado was contacted to have public utilities marked, as required by law. Notices of Intent to Construct Monitoring Holes and Monitoring Well Permit Applications were prepared and submitted to the Colorado State Engineer's Office. A project-specific Health and Safety Plan was prepared to address potential safety concerns associated with the work. Tetra Tech was present to oversee, direct and document all drilling and monitoring well installation activities. A hydrogeologist was present to collect and log geologic samples of drill cuttings.

The three borings were advanced through surficial (artificial, alluvial, and colluvial) deposits using a combination of techniques to prevent borehole collapse or to serve as surface conductor casing. Well Nests 1 and 3 were initially drilled using an 8-inch ODEX system that drove a temporary casing to depths of 58 and 37 feet in Well Nests 1 and 3, respectively. Well Nest 2 was initiated using air-rotary technology and a 7 7/8-inch bit to install 6 ½ -inch conductor casing to a depth of 16 feet below ground surface (ft bgs). The temporary casing was removed during final well construction. Drilling continued below the temporary casing to total depth using air-rotary technology. The borehole diameter to total depth in Well Nests 1 and 3 was 8 inches. The borehole to total depth in Well Nest 2 was 5 7/8-inches in diameter. Samples of subsurface materials were collected during drilling; however, the samples were in the form of disturbed drill cuttings.

Well Nest 1 (MW-1A and MW-1B)

Drilling and installation activities for Well Nest 1 were initiated on November 4, 2010 and completed on November 9, 2010. The borehole was advanced to a total depth of 605 ft bgs. Lithologies encountered during drilling of the Well Nest 1 borehole consisted of colluvial silty, sandy gravels to a depth of approximately 40 ft bgs. Below this, the borehole encountered predominantly siltstone with interlayered, fine-grained sandstone, consistent with the recognized lithologies of the Shire sub-member of the Atwell Gulch member of the Wasatch Formation. During drilling/well installation of the nested wells at MW-1, a natural gas drilling rig was observed in operation approximately 700 feet northeast of the location.

Well Nest 2 (MW-2A and MW-2B)

Drilling and installation activities for Well Nest 2 were initiated on January 19, 2010 and completed on January 27, 2010. The borehole was advanced to a total depth of 605 ft bgs. Lithologies encountered during drilling of the Well Nest 2 borehole consisted of predominantly siltstone, consistent with the recognized lithologies of the Shire sub-member of the Atwell Gulch member of the Wasatch Formation. Evidence for the presence of the coarser Molina-like member described by Donnell (Donnell, 1969) and recognized in the URS Phase I report for the area was not noted in the lithologic log.

Well Nest 3 (MW-3A and MW-3B)

Drilling and installation activities for Well Nest 3 were initiated on October 18, 2010 and completed on October 23, 2010. The borehole was advanced to a total depth of 590 ft bgs. Lithologies encountered during drilling of the borehole for Well Nest 3 consisted of predominantly siltstone with interlayered, fine-grained sandstone, consistent with the recognized lithologies of the Shire sub-member of the Atwell Gulch member of the Wasatch Formation.

3.3 Geophysical Logging

Drilling using air to circulate the cuttings makes stratigraphic identification increasingly difficult with depth because of potential increased mixing of cuttings during air-entrainment between the formation and surface. To improve identification of stratigraphic markers, geologic characteristics and to facilitate stratigraphic correlations, geophysical logging was performed in each of the completed borings. These techniques allow identification and differentiation of downhole stratigraphy and correlation with the lithologic log.

Well Nest 1

Downhole geophysics were conducted following the drilling of the borehole for Well Nest 1 on November 4, 2010. The geophysical suite included 3-arm caliper and borehole deviation, short- and long-normal electrical resistivity, spontaneous potential (E-Logs), natural gamma, and neutron. The geophysical logs recorded for Well Nest 1 are provided in Appendix A.

Well Nest 2

Downhole geophysics were conducted following the drilling of the borehole for Well Nest 2 on January24, 2010. The geophysical suite included 3-arm caliper and borehole deviation, E-Logs, natural gamma, neutron and water temperature (Nest 2 only). The geophysical logs recorded for Well Nest 2 are provided in Appendix A.

The borehole for Well Nest 2 only contained fluid to a depth of 530 ft bgs at the time of geophysical logging. Geophysical signals associated with electrical conductance, including SP, and the electrical resistivity tools were inconsistent at depths less than 530 ft bgs as the electrodes were suspended in air, rather than in fluid in the borehole. Gamma and neutron tools recorded effective data, although their results are more complicated to interpret without the corresponding E-Logs.

Well Nest 3

Downhole geophysics were conducted following the drilling of the borehole for Well Nest 3 on October 20, 2010. The geophysical suite included 3-arm caliper and borehole deviation, E-Logs, natural gamma, and neutron. The geophysical logs recorded for Well Nest 3 are provided in Appendix A.

At the time of geophysical logging, the borehole for Well Nest 3 contained fluid at a depth of approximately 223 ft bgs. The geophysical signals associated with the E-Logs are intermittent and/or attenuated at shallower depths than 223 ft as a result.

3.4 Well Installation and Completion Details

As-built well construction diagrams are provided with the well logs in Appendix B. Each well nest consisted of two monitoring wells. In each of the nests, the shallow and deep wells were completed at approximate depths of 400 and 600 ft bgs, respectively. Well centralizers were placed at regular intervals, including immediately below and above the screened intervals to ensure that the well column was located in the center of the borehole and to permit annular materials to completely surround the well casing. A filter pack consisting of 10/20 silica sand was placed using tremie pipe adjacent to the well screen and extended approximately 2-10 feet above and 2 feet below the screen.

The deeper well was constructed first by lowering the well screen and blank casing to the design depth. The filter pack sand was then placed at the design depth and measured using a weighted tape. A bentonite seal was placed by slowly pouring slow-release pellets through the borehole annulus until the seal extended approximately 3 feet above the top of the filter pack, as confirmed by measurement with a weighted tape. Cement-bentonite grout was tremied above the seal to a depth of approximately 5 feet below the shallow well screen. The grout was allowed to cure for a minimum of 12 hours.

A 3-foot bentonite seal was placed on top of the cured grout by slowly pouring slow-release bentonite pellets through the borehole annulus. The bentonite seal placement depth was confirmed using a weighted tape. The bentonite was allowed to hydrate for a minimum of one hour before the upper well screen and casing were placed at their design depth (2 feet above the bentonite). After the well screen and casing were placed, the second filter pack was placed as described above. A bentonite seal, approximately two feet thick was placed above the filter pack for the upper screen, and the remainder of the borehole was tremie grouted to ground surface using a cement-bentonite mixture. The temporary surface casing was removed as the upper 40 feet of the borehole was grouted.

After well construction had been completed, dedicated bladder pumps were installed in each of the new monitoring wells. The pumps were set in the wells so the pump intakes are centered in the screened interval.

Well Nest 1

Well MW-1A was constructed using 2-inch, Schedule 80, flush-threaded PVC with 20 feet of 10-slot well screen from 378.5 to 398.5 ft bgs and a five-foot sediment sump constructed of unslotted casing. Well MW-1B was constructed using 2-inch, Schedule 80, flush-threaded PVC with 10 feet of 10-slot well screen from 584.2 to 594.2 ft bgs and a five-foot sediment sump constructed of unslotted casing.

Well Nest 2

Well MW-2A was constructed using 2-inch, Schedule 80, flush-threaded PVC with 20 feet of 10-slot well screen from 375 to 395 ft bgs and a five-foot sediment sump constructed of unslotted casing. Well MW-2B was constructed using 2-inch, Schedule 80, flush-threaded PVC with 10 feet of 10-slot well screen from 588 to 598 ft bgs and a five-foot sediment sump constructed of unslotted casing.

Well Nest 3

Well MW-3A was constructed using 2-inch, Schedule 80, flush-threaded PVC with 10 feet of 10-slot well screen from 375 to 385 ft bgs and a five-foot sediment sump constructed of unslotted casing. Well MW-3B was constructed using 2-inch, Schedule 80, flush-threaded PVC with 10 feet of 10-slot well screen from 575 to 585 ft bgs and a five-foot sediment sump constructed of unslotted casing.

3.5 Well Surface Completion and Development

The final monitoring well casings were cut to just below ground surface. The two wells in each nest were both protected in traffic-rated flush-mount surface vaults secured with tamper proof bolts. The vaults were set in 2-foot by 2-foot by 6-inch thick reinforced concrete pads. The pads were completed 3 inches above existing grade with the apron tapered 2 inches lower such that precipitation runoff will flow away from the well. Matching keys for each well nest were furnished to the County.

After well installation had been completed, each of the well nests and top of casing elevations for both wells in the nests were surveyed by a Professional Land Surveyor licensed and registered in the State of Colorado. Each of the wells in the nest was surveyed for horizontal location to within ± 1 meter and elevation to within ± 0.01 feet. Table 1 contains a summary of the survey data. The wells were developed by air-lifting no sooner than 24 hours after installation to remove formation material and residual well construction fines from the sampling interval of the well, and improve hydraulic connectivity with the formation. Attempts were made to conduct well development, with the goal of producing water from each well until pH, temperature, and conductivity were stable and the produced water is visually clear, to a maximum of 5 wetted well casing volumes. Limited water production from the monitoring wells prevented the removal of the desired 5 casing volumes. The lack of water production and inability to fully develop the wells was a result of the low formation permeability and the fact that small screen intervals were used to collect samples from discrete depth intervals.

Well Nest 1

Well development activities for MW-1A and MW-1B were conducted on December 15 and 16, 2010. During development of MW-1A, air-lifting was utilized to purge a total of approximately 11 gallons of water. Field notes indicate that the water initially appeared "foamy" in the water tank. Water quality measurements noted at the completion of development of MW-1A consisted of an electrical conductivity of 3,665 µS/cm, a pH of 10.23, and visual turbidity in the water being purged. Approximately one well-volume of water was removed on December 15, 2010 prior to the well going dry, and an additional gallon was purged on the second day prior to again going dry. Fluid flow into the well proved insufficient (less than 0.1 gpm) to perform complete hydraulic well development.

During development of MW-1B, air-lifting was utilized to purge approximately 27 gallons of water. Field notes indicate that a faint sheen was noted in the development water holding tank. The source of the sheen is unknown. Water quality measurements noted at the completion of development of MW-1B consisted of an electrical conductivity of 4,580 µS/cm, a pH of 9.79, and a light-brown color to the water being purged. Approximately one well-volume of water was removed on December 15, 2010, and an additional 6 gallons were purged on the second day. Fluid flow into the well proved insufficient (less than 0.1 gpm) to perform complete hydraulic well development.

Well Nest 2

Well development activities for MW-2A and MW-2B were conducted on February 1 and 2, 2010. During development of MW-2A, air-lifting was utilized to purge a total of approximately 60 gallons of water, or approximately 1.2 well-volumes of water. Water quality measurements noted at the completion of development of MW-2A consisted of an electrical conductivity of 1,730 µS/cm, a pH of 10.05, and visual turbidity in the water being purged. Approximately one well-volume of water was removed on February 1, 2010, and an additional 6 gallons were purged on the second day. Fluid flow into the well proved insufficient (less than 0.1 gpm) to perform complete hydraulic well development.

During development of MW-2B, air-lifting was utilized to purge approximately 82 gallons of water. Field notes indicate that the water initially appeared "sudsy" in the water tank. Water quality measurements noted at the completion of development of MW-2B consisted of an electrical conductivity of 2,150 µS/cm, a pH of 9.7, and a brown color to the water being purged. Turbidity remained high throughout the purge process as water consistently contained significant silt content. Approximately one well-volume of water was removed on February 1, 2010, and an additional 2.25 gallons were purged on the second day. Fluid flow into the well proved insufficient (less than 0.1 gpm) to perform complete hydraulic well development.

Well Nest 3

Well development activities for MW-3A and MW-3B were initially conducted on October 10, 2010. During development of MW-3A, air-lifting was initially utilized to purge a total of approximately 62 gallons of water, or approximately 1 well-volume of water. Field notes indicate that the water initially appeared "soapy" in the water tank. A second round of development was conducted on December 16, 2010 by which time the water level in the well had only recovered to 40 ft above the top of the screened interval. Water quality measurements noted at the completion of development of MW-3A consisted of an electrical conductivity of 6,130 µS/cm, a pH of 10.09, and visual turbidity in the water being purged. Fluid flow into the well proved insufficient (less than 0.1 gpm) to perform complete hydraulic well development.

During development of MW-3B, air-lifting was utilized to purge approximately 119 gallons of water. During October 10, 2010 development of MW-3B, air-lifting was initially utilized to purge a total of approximately 95 gallons of water, or approximately 1 well-volume of water. A second round of development (29 gallons purged) was conducted on December 16, 2010 by which time the water level in the well had only recovered to 140 ft above the top of the screened interval. Water quality measurements noted at the completion of development of MW-3B consisted of an electrical conductivity of 5,320 µS/cm, a pH of 9.99, and a brown color to the water being purged. Turbidity remained high throughout the purge process as water consistently contained significant silt content. Fluid flow into the well proved insufficient (less than 0.1 gpm) to perform complete hydraulic well development.

Following development procedures, it was noted that a handful of what appeared to be filter-pack material had come out of MW-3B along with the development water. This could indicate that filter material got accidently introduced to the casing during well construction, or that the well screen may have been compromised. The integrity of the bottom of the well sump was verified following development, although the condition of the well screen could not be. Subsequent measurements of well depth during sampling indicate that the well does not appear to be filling with sediment, suggesting that the well screen remains functional.

3.6 Well Redevelopment

During the initial two groundwater sampling events, several water quality parameters including pH, alkalinity, and TDS were observed to vary significantly from the range anticipated to be present. Although the wells were designed and constructed using methods described in the County-approved, project-specific QAPP and EPA-accepted protocols, including those with concern for cross-contamination between aquifers, it appears that cement-grout used during well construction may be impacting the chemistry of the nested-well groundwater quality.

Cement grout used in sealing the annular space in each of the well nests consists of a mix of cement and water. The cement component is a mix of lime, silica, alumina and iron oxides, and gypsum. When hydrated, the pH of the fluids associated with the cement is highly alkaline (pH around 13) due to dissolution of the lime. In an alluvial aquifer through which significant volumes of water move, residual fluids related to grouting of a well are likely dissipated through dilution and reaction with the more neutral pH of the groundwater. If alkaline fluid associated with the grout invades the fractures of a low-permeability formation such as the siltstones present in the study area, the fluid may not be diluted or neutralized naturally, and may continue to elevate the pH in the well for a significant period of time.

Field measured pH values are consistently above 10, values that are higher than other measured water chemistry observed in the Mamm Creek Study Area. TDS and alkalinity are also high relative to expected concentrations. Grout or high-pH, high alkalinity water from grouting activities may have seeped into fractures in the surrounding formation, contacting groundwater as it enters the well during well purging/sampling.

The data indicated that fluids related to the emplacement of cement-grout seal had spread into the fracture network surrounding the wells. Efforts to improve pH in the wells included two well redevelopment events. During both March 2012 and May 2012, each of the three nested well sets were surged, then bailed to remove as much water as possible in an attempt to enhance flow into the wells from surrounding fractures and to remove any high pH related particulate matter in the well. During the second of the two well development events, water obtained from the Town of Silt municipal water supply was used in an attempt to improve well conditions. Groundwater in each well was initially purged during this process, followed by the addition of Silt municipal water and a subsequent period of surging followed by purging of the water remaining in the wells. By first removing the existing high pH water and suspended particulate matter, surging with additional water was intended to further mobilize and remove the high pH fluid in the surrounding fracture network. Laboratory reports for two samples collected from the Silt municipal water source are provided in Appendix C.

3.7 Investigation Derived Waste Management

Since the wells were located on private land, investigation derived waste (IDW) generated during drilling and well development was containerized. Solids and liquids were transported for disposal at the Williams Production RMT Oil and Gas Wastewater facility in Parachute, Colorado.

As a result of groundwater sampling using low flow methods, minimal quantities of purge water were generated. The purge water was assumed not to be contaminated, and this “de minimis” quantity of water was not anticipated to have a negative impact on private property (erosion, mud, etc.); therefore, the purge water generated during sampling was discharged to the ground.

3.8 Groundwater Sampling

Groundwater sampling was conducted using methods described in the County-approved, project-specific Quality Assurance Project Plan (QAPP) (GeoTrans, 2011) and EPA-accepted protocols.

These sampling methods include provisions for low-flow water quality sampling, a process by which water is purged from the well at a rate which will not lead to turbulent flow within the well screen, encouraging flow to occur directly from the formation to the pump with minimal mixing in the water column in the well itself. The project QAPP and EPA procedures for low flow sampling target a steady flow rate while maintaining a drawdown of less than 0.33 feet, but also note that the goal of a drawdown of less than 0.33 feet may be difficult to achieve due to some geologic heterogeneities and may require adjustment based on site-specific conditions. In most cases, the drawdown during low-flow sampling of the Phase III wells was greater than 0.33 feet. Similar to the lack of water production during development, the drawdown in the wells was a result of the low formation permeability and the fact that small screen intervals were used to collect samples from discrete depth intervals.

Low-flow water quality samples were collected using the dedicated conventional air-powered bladder sampling pumps that had been installed during the first groundwater sampling event. Samples were field filtered to 0.45μ when necessary for analysis of dissolved parameters. Groundwater gas samples were collected using the bladder pump with discharge directed through a bleed valve to eliminate air from the sampling system and a small pressure surge tank to reduce in-line pressure variations. The dissolved-gas samples were collected in Tedlar bags that were pre-preserved with a biocide capsule, and purged of air during the sampling process.

Four groundwater sampling events were conducted between January 19, 2011 and December 20, 2012. Water level measurements and water quality samples were collected from each of the six monitoring wells in the three well nests, as well as the Currie Well, a domestic well with a measured total well depth of 406 ft. A dedicated bladder pump was also installed in the Currie Well). The following analyses were performed on the groundwater samples:

Field Parameters
Dissolved oxygen
pH
Specific conductance
Temperature
Oxidation reduction potential

Hydrocarbons
BTEX
TPVH (GRO)

Dissolved Gases
Argon
Butane with isomers
Carbon dioxide

General Chemistry/Metals
Alkalinity
Ammonia
Barium
Calcium
Chloride
Total coliform
Hydrogen sulfide
Iron (Ferric, Ferrous and Total)
Magnesium
Manganese
Nitrate
Nitrite
Potassium
Sodium

Ethane
Helium
Methane
Nitrogen
Oxygen
Pentane with isomers
Propane

Strontium
Sulfate
Total dissolved solids

Isotopic Analysis

Methane isotopic ratios of carbon and hydrogen molecules to differentiate methanogenic sources.

One field duplicate sample was collected during each sampling event for hydrocarbons and general chemistry parameters and one trip blank accompanied the samples during each event. The duplicate was not analyzed for isotopic composition to reduce program costs.

During groundwater sampling activities, the field notes recorded for the January 2011 event indicate that the purge water from MW-2A and MW-3B effervesced. Also, during the May 2011 event, purge water from MW-1A, MW-2A, MW-3A effervesced. During the August 2012 and December 2012 event, purge water from MW-2A effervesced and a sulfur-type odor was noted. A sulfur-type smell was noticed during collection of the sample from the Currie Well during all four sampling events.

Groundwater conditions were generally observed to be consistent with reducing chemistry. Dissolved oxygen in monitored field parameters were typically < 1 mg/L with the exception of the initial (January 2011) sample collected from each well, and the MW-3B samples. These appear likely to have had some atmospheric interaction either during development/installation or due to water source in the case of MW-3B. Oxidation-reduction potentials were generally negative, and the observed sulfur-type smells are typical with those associated with hydrogen sulfide, the reduced form of sulfur.

4.0 PHASE III DATA SUMMARY

Data generated during this investigation included water level and water quality data that were obtained during the four sampling events. These data are presented in this section. Section 5.0 provides interpretation for the data.

4.1 Potentiometric Data

Water level data generated during all four sampling events and additional water-level collection events are summarized on Table 2. Interpreted groundwater elevation contours for the shallow wells as measured during the two 2011 and two 2012 sampling events are provided on Figures 5a, 5b, 5c and 5d, respectively. Interpreted groundwater elevation contours for the deep wells as measured during the two 2011 and two 2012 sampling events are provided on Figures 6a, 6b, 6c and 6d. A water-level elevation time series plot for the Phase III wells is provided in Figure 7.

4.2 Analytical Results

Laboratory analytical data generated during all four sampling events is summarized on Tables 4, 5a, and 5b and the laboratory reports for all sampling events from Accutest Mountain States Laboratories, Test America, and Isotech Laboratories are included in Appendix C. Seven well samples (one from each nested well plus the Currie Well) were collected during each of the 2011 sampling events. After redevelopment, the depth to water in well MW-2B was greater than the pump capacity and samples could not be collected in 2012. Quality assurance and quality control (QA/QC) samples in the form of field duplicate samples were also collected for organic, inorganic, and general chemistry parameters. Field duplicate samples were collected from MW-2A during the January 2011 event, MW-1B during the May 2011 event, and MW-1A during the August 2012 and December 2012 events. The results of the duplicate analysis are included on Table 6 along with the results of the parent sample analysis. A discussion of the QA/QC sample results is included in Section 5.12.

4.3 Water Quality Characteristics

Analytical results from all well nest samples and the Currie Well samples are provided on Table 4, which also lists relevant Colorado and EPA primary and secondary drinking water standards. Analytical results for each of the samples were compared with these standards. Results above standards are highlighted in yellow on the table. It should be noted that the Colorado basic standards for groundwater (BSGW), secondary drinking water standard for TDS is based on a sliding scale. For background TDS concentrations between 0 and 500 mg/L, the standard is 400 mg/L or 1.25 times the background concentration, whichever is least restrictive. For background TDS concentrations between 501 and 10,000 mg/L, the standard is 1.25 times the background concentration. For background TDS concentrations greater than 10,001 mg/L, numerical standards do not apply. Background levels are established by working with the Colorado Water Quality Control Commission, and this process was beyond the scope of this investigation. Therefore, a concentration of 400 mg/L was used as a reference standard for TDS in this report.

4.3.1 Water Type Classification

Generally the water chemistries reflect classifications that fit in the category of Na-CO_3-Cl, NaCl-CO_3, or in the case of the Currie Well, Na-SO_4-Cl. Alkalinity concentrations for the nested monitoring wells, reported as alkalinity as $CaCO_3$, have been assumed to consist entirely of a combination of the hydroxide (OH^-) ion and CO_3^{2-} ion in solution since measured pH values in the nested wells were all at or above 10.3, the approximate equilibrium pH at which acid-neutralizing capacity is equal between the hydroxide ion and the carbonate ion. An exception is the alkalinity parameters observed during the 2012 sampling events in MW-2A. In this well, redevelopment activities performed during the first half of 2012 were successful in improving conditions reducing pH values to near 8.5. In monitoring well MW-2A, water chemistry reflects the classification of Na-Cl-SO_4.

pH

The initial pH range of samples (12.1 to 12.9) collected from the three new well nest locations during January and May 2011 were higher than the typical values reported for the other wells at similar depths within the Wasatch Formation. The cause of these high values is uncertain, but is most likely related to either local formation water or to factors related to well construction. It was observed that during initial well development, pH values commonly stabilized in the 9 to 10 range, suggesting that the pH values associated with the water quality samples collected during the January and May 2011 events may be higher than those in the surrounding groundwater.

Following well redevelopment activities performed in March and May 2012, pH values in MW-2A declined to below 9. Each of the other wells continued to have pH observations consistently above 10. Field-measured conductivity values in each well declined after redevelopment in March and May 2012 suggesting that redevelopment activities were partially successfully at removing dissolved solids believed to be the result of cement-grout in the surrounding fracture network. Although efforts were made to further well and formation development to remove water quality impacts associated with potential grout intrusion in bedrock fractures, with the exception of MW-2A, the wells in the three nested well locations continue to contain high pH water.

4.3.2 Comparison to Water Quality Standards

Analytical results from all well nest samples and the Currie Well samples are provided on Table 4, which also lists relevant Colorado and EPA primary and secondary drinking water standards. Analytical results for each of the samples were compared with these standards. Results above standards are highlighted in yellow on the table. The laboratory analytical reports are provided in Appendix C.

Volatile organic compounds (VOCs) results above standards were limited to one sample collected from MW-1B in January 2011 in which a benzene concentration of 5.3 µg/L was measured, which is above the MCL of 5 µg/L. Benzene was reported above the laboratory reporting limit but below the MCL in most of the samples collected during the Phase III investigation.

Concentrations of barium above the 2,000 µg/L MCL were limited to two samples from MW-3A in January 2011 and May 2011, in which barium concentrations of 5,600 µg/L and 5,760 µg/L were measured, respectively. All sample results were above the 500 mg/L National Secondary Drinking Water Standard for TDS and the 400 mg/L Colorado BSGW, secondary drinking water standard for TDS. TDS was detected at concentrations ranging from 1,600 mg/L in well MW-1A in August 2012 to 11,200 mg/L in well MW-3A in May 2011. All sample results were above the 250 mg/L National Secondary Drinking Water Standard and Colorado BSGW, secondary drinking water standard for chloride, with the exception of well MW-1A in January 2011 (172 mg/L), August 2012 (240 mg/L), and December 2012 (190 mg/L). Chloride in the other samples ranged from 397 mg/L in the Currie Well in January 2011 to 2,780 mg/L in MW-3A in May 2011.

The only other detection above standards was sulfate in the Currie Well and in MW-2A. Sulfate was detected at concentrations of 681 mg/L, 604 mg/L, 560 mg/L, and 560 mg/L in January 2011, May 2011, August 2012, and December 2012 respectively in Currie Well. Sulfate was detected at concentrations of 510 mg/L, and 270 mg/L in August 2012, and December 2012 respectively, above the National Secondary Drinking Water Standard and Colorado BSGW, secondary drinking water standard of 250 mg/L.

4.3.3 Methane in Groundwater

Although there is no regulatory standard for methane in groundwater, high concentrations of methane in groundwater can potentially accumulate and pose an explosive hazard in basements or other spaces with restricted ventilation. The COGCC recommends that groundwater samples found to contain methane concentrations greater than 2 mg/L be submitted for analysis of stable isotopes of carbon and hydrogen to evaluate it's likely source (COGCC, Rule 608b(3)). The USGS (USGS, 2006) and the U.S. Department of Interior, Office of Surface Mining (Eltschlager, et al., 2001) recommend additional investigation for dissolved methane concentrations above 10 mg/L. Dissolved gas and isotopic analytical results from all well nest samples and the Currie Well samples are provided on Table 5a, and dissolved methane and isotopic results are also summarized separately on Table 5b.

Methane was detected in every groundwater sample collected. Methane concentrations in groundwater collected during the January 2011 sampling round ranged from 0.36 mg/L in MW-3B to 84 mg/L in MW-3A. Methane concentrations in groundwater collected during the May 2011 sampling round ranged from 0.81 mg/L in MW-3B to 66 mg/L in MW-3A. Methane concentrations in groundwater collected during the August 2012 sampling round ranged from

0.53 mg/L in MW-3B to 140 mg/L in in MW-2A. Methane concentrations in groundwater collected during the December 2012 sampling round ranged from 2.3 mg/L in MW-3B to 130 mg/L in MW-2A. These data are presented graphically on a map in Figure 8. Figure 16 includes methane concentrations in other wells from the study area. Time-series plots for methane in Phase III wells and in wells located within a mile of the Phase III wells are presented in Figures 17 and 18.

4.3.4 Other Water Quality Parameters

Methane Carbon and Hydrogen Isotopes

Analysis of stable isotopes of carbon ($\delta^{13}C_1$) and hydrogen (deuterium; δDC_1) was performed on dissolved methane gas extracted from groundwater samples collected during the all monitoring events. January 2011 $\delta^{13}C_1$ values ranged from -82.03 permil (‰) in the Currie Well to -36.33 ‰ in MW-1B. May 2011 $\delta^{13}C_1$ values ranged from -80.19 ‰ in the Currie Well to -37.21 ‰ in MW-1B. August 2012 $\delta^{13}C_1$ values ranged from -81.1 (‰) in the Currie Well to -53.90 (‰) in MW-3B. December 2012 $\delta^{13}C_1$ values ranged from -80.09 (‰) in the Currie Well to -37.17 (‰) in MW-1B.

January 2011 δDC_1values ranged from -211.4 ‰ in MW-3A to -170.4 ‰ in MW-1B. May 2011 δDC_1values ranged from -208.6 ‰ in MW-2A to -177.3 ‰ in MW-1B. August 2012 δDC_1 values ranged from -208.8 (‰) in MW-2A to -180 (‰) in MW-1A. December 2012 δDC_1 values ranged from -208 (‰) in MW-2A to -160.6 (‰) in MW-1B. A summary of the analytical results for the isotopic analyses is provided in Tables 5a and 5b.

Wet Gas Compounds

Wet gas analysis was conducted on the samples collected from the all of the wells, and is provided in Table 5a. The methane results are also provided separately on Table 5b. Wet gas molar percentages of two-carbon chain molecules were measured in each of the samples collected from each of the wells at molar percentages ranging from 0.0037 % in the sample collected in the Currie Well in January 2011 to 1.41% in the sample collected from MW-1B in May 2011. C_3 hydrocarbon molecules and ethane (C_2H_4) concentrations have been measured above the detection limit in each of the wells except for the Currie Well. Propane isomers (iC_4 and nC_4) were detected in all the wells except for MW-2B, and Currie Well. No detections occurred for the five-carbon “condensate” molecules except for MW-1B with a detection of 0.0002 % in December 2012. The C_6+ “condensate” molecules ranged from non-detect to 0.0019 % in MW-1B during the August 2012 event.

Chloride

The National Secondary Drinking Water Standard and Colorado BSGW, secondary drinking water standard for chloride is 250 mg/L. Concentrations of chloride observed in the nested wells installed during the Phase III investigation are provided in Table 4, in map view on Figure 9 and in time series on Figure 15b. They range from 172 mg/L in MW-1A in January 2011 to 2,780 mg/L in MW-3A in 2011. Chloride concentrations averaged 861 mg/L in the shallow wells, and 1,211 mg/L in the deep wells.

Total Dissolved Solids (TDS)

As noted in Section 4.3, the Colorado BSGW, secondary drinking water standard for TDS is based on a sliding scale, and a concentration of 400 mg/L was used as a reference standard for TDS in this report. Concentrations of TDS observed in the nested wells installed during this phase of work are provided in Table 4. They range from 1,600 mg/L in MW-1A in August 2012 to 11,200 mg/L in MW-3A during the May 2011 sampling event. TDS in the Phase III nested wells is generally considered to be influenced by grout-intrusion into fractures during well construction, and is not useful for comparison to external data sources with the exception of the 2012 water samples collected from MW-2A.

5.0 DATA INTERPRETATION

5.1 Wasatch Formation Conceptual Hydrogeologic Model

Groundwater flow in layered sedimentary stratigraphy occurs predominantly in a horizontal direction within the higher permeability silts, sands or gravels of an unconsolidated alluvial aquifer, or through a moderate to high permeability sandstone matrix in a lithified stratigraphy. In these conceptual models, flow occurs evenly throughout the aquifer material arriving at the pumped well in a convergent radial pattern.

The conceptual model of groundwater flow in the Wasatch Formation is somewhat different. In the Wasatch Formation, the stratigraphy commonly consists of low-permeability siltstones and mudstones through which groundwater flow is significantly impeded. Locally isolated lenses of slightly higher permeability sandstone may be present within these finer-grained layers. In the study area, the Wasatch Formation is in addition characterized by fractures and faults associated with the Divide Creek anticline, some of which have been mapped as part of past hydrogeologic characterization documented in the Phase I study (URS, 2006). These fractures can provide permeability and conductivity enhancements of several orders of magnitude over the permeability of the associated matrix rock (Lorenz, Nadon and LaFreniere, 1996). It is likely that groundwater flow through the rocks of the Wasatch Formation in which the nested wells have been installed, occurs primarily within these fractures. This conceptual flow model with groundwater primarily flowing within fractures implies that portions of the Wasatch Formation present between fractures exist as structurally intact, low permeability rocks, potentially containing lenses of sandstone. Interpretation of gas or liquid in the Wasatch Formation has been conducted within this context.

The Wasatch Formation is a source of both potable and non-potable water and also contains rich natural gas deposits (URS Corporation, 2006). Natural gas has been observed to be present within the sandstone lenses of the Wasatch Formation near the towns of Parachute and Rulison (Nelson and Santus, 2010). The Molina Member represents the principle target within the Wasatch Formation for natural gas exploration (Lorenz, Nadon and LaFreniere, 1996).The shallow stratigraphy may therefore contain isolated pockets of gas which have been locally present for thousands of years or more, and may not be associated with a deeper genesis.

Gas and/or groundwater may also migrate within the fracture conduits in the bedrock, with an orientation, which may lead to unexpected flow directions including following vertical pathways and/or angular changes in direction laterally. An example of this type of fracture flow path is suspected in West Divide Creek seep. The gas production well Schwartz 2-15B is believed to have intercepted a natural fault during drilling, and a drop in production casing cement led to lateral migration of Mesa Verde Formation-sourced methane from the well bradenhead along natural fractures to its emergence approximately ½ to ¾ mile away in the stream bed of West Divide Creek in the form of gas seepage (Andrews, 2009 and Baer and Williams, 2009).

5.2 Lithostratigraphic Interpretation

The lithologies encountered in the boreholes for Well Nests 1, 2 and 3 generally consisted of interbedded fine-grained gray to brown sandstones and siltstones. Cuttings were logged as they came out of the rotary wash. Although the chip cuttings are expected to be representative of the formations in the subsurface, they do not provide any information about the nature of subsurface fracturing. The siltstones and sandstones generally are fine-grained, well sorted and interbedded. These observations are consistent with lithologies of the Shire sub-member of the Atwell Gulch Member of the Wasatch Formation. Although the upper section of Well Nest 2 would have been expected to encounter the Molina-like member of the Shire, a section of the Shire "distinguished by the presence of 20 percent sandstone beds that are more resistant than those of the Shire because they are thicker and more strongly cemented by calcium carbonate" (Shroba and Scott, 1997 and 2001), the cuttings observed in the borehole from Well Nest 2 do not appear to have encountered this in the upper portion.

The fine-grained nature of the siltstones and sandstones, particularly where cemented, would generally be expected to be poor conductors of water due to low hydraulic permeability. Secondary porosities associated with high-angle fracture sets likely represents a significant influence on groundwater flow, vertically and horizontally within the Atwell Gulch Member in which the Phase III investigation wells are screened.

The suite of geophysical logs conducted at each borehole was identified in Section 3.3 above. The geophysical logs do not provide much additional information for interpretation beyond that provided by the lithologic logs. Gamma logs represent downhole measurements of naturally occurring gamma radiation emitters, typically consistent with clays and shales. The gamma logs generally support the drill cuttings observations which were interpreted as a sequence of interlayered siltstones/mudstones and sandstones. The gamma logs also helped define thicknesses for individual lithologic layers. Where available, the E-Logs are/were useful for confirming depths and thicknesses of sandstones within sequences of finer-grained mudstones. The caliper logs may be most valuable in that they indicate where fracture sets that intersect the boreholes at depth.

In the borehole for Well Nest 1, the caliper log indicates potentially significant fractures at depths of 100 ft and 180 ft bgs. Minor variations occur intermittently from 60 ft to 240 ft bgs and may represent smaller fractures. The borehole is relatively consistent in diameter from 240 to 600 ft bgs, with additional minor changes, potentially representative of fractures at 365 ft, 382 ft, 463 ft, and from 575 to 587 ft bgs. Potential fractures are present in the borehole caliper log for Well Nest 2 at depths of 160 ft, 516 ft, and 527 ft bgs. Potential fractures are present in the borehole caliper log for Well Nest 3 at depths of 316 ft, 322 ft, 342 ft, and 355 ft bgs.

Based on the lithologic and geophysical interpretations, screened intervals for each of the three Well Nests were completed in a fine-grained sandstone unit, identified as the Shire sub-member of the Atwell Gulch Member of the Wasatch Formation.

5.2 Potentiometric Data Interpretation

Table 2 summarizes potentiometric surface elevations for the wells in Well Nests 1, 2, and 3 and in the Currie Well, as measured during each of the nine water-level monitoring events conducted during 2011 and 2012. In the Phase I study report, URS constructed a potentiometric surface elevation map for the shallow wells in the Mamm Creek study area. An evaluation of the potentiometric surface represented by the water levels in the Phase III wells was conducted for each of the water-level monitoring events associated with the four water quality sampling events of January 2011, May 2011, August 2012, and December 2012. Potentiometric contours are drawn alongside the more regionally extensive potentiometric surface contouring from the Phase I study report to provide regional context for the local flow interpretation. The interpreted potentiometric surfaces for the shallow wells of the well nests (MW-1A, MW-2A and MW-3A and the Currie Well) are provided in Figures 5a to 5d. Evaluations of the potentiometric surface associated with the water levels in the deep wells (MW-1B, MW-2B and MW-3B) are provided in Figures 6a to 6d.

The conceptual model of the hydrogeology in the depth intervals associated with the investigation wells is that of low-permeability siltstones and sandstones which contain intermittent fracture patterns which may or may not be laterally or vertically continuous over short distances. Within this hydrogeologic framework, groundwater flow originates as precipitation in higher elevation areas and flows toward lower elevation areas such as the nearby stream network. The shallow-well water elevations results are consistent with this conceptual model. Based on water elevations in these wells, flow is interpreted to be generally to the north and locally away from the higher elevation land surfaces and toward either Dry Hollow Creek near the Currie Well, or Divide Creek near each of the other well nests. The anticipated flow direction would be generally to the north, in the direction of decreasing topographic elevation and toward the Colorado River, the regional drainage.

Figure 7 presents the water-level elevations for the Phase III wells during 2011 and 2012. While little water-level variation over time occurs in the Currie Well, water levels in each of the nested wells exhibit some degree of variation, a behavior which is believed to provide insight into the water sources that influence them.

Water levels in the Currie Well have remained relatively stable during each of the water level monitoring event, varying by less than 2 feet. Minimal water level variation in an area of significant seasonal surficial hydrologic change suggests a nearby constant water source independent of the seasonal change. Unlike the Phase III investigation nested wells, the Currie Well is likely completed with a long well-screen to maximize the water flow into the well from the surrounding, low-permeability formation. This increases the exposure of the well to the fractures present locally, increasing the well yield. Additionally, the Currie Well is located within approximately 300 feet of a surface impoundment caused by a dammed drainage. Slow but constant infiltration of water from this impoundment could serve to stabilize water levels locally as the regional groundwater flow pattern continues to drain to Dry Hollow Creek. Although this observed response to a nearby surface water feature contributes to the conceptual model of groundwater flow by demonstrating surface-groundwater connection, Currie Well observations may not assist significantly in the interpretation of observations in other wells in this investigation as a result.

MW-1A shows a nearly 300-ft potentiometric rise from between May 2011 and January 2012 suggesting a possible connection to infiltration associated with spring snowmelt run-off, either due to increased stream stage in nearby Divide Creek, or due to infiltration of snowmelt directly into local fractures which then connect to the well The water levels then decline until the well redevelopment event in May 2012, after which water levels decline precipitously to elevations that resemble those measured in January 2011. Water levels in MW-1B are consistently lower than those in MW-1A, but behave in a similar fashion to MW1A, rising in elevation between May 2011 and January 2012, then declining after the redevelopment event in May 2012, and ultimately stabilizing at elevations similar, or slightly higher than those observed at the end of 2010. Redevelopment activities included complete evacuation of water from each well, and likely also evacuated all water which could easily drain from the nearby fracture network into the well. Water levels measured within weeks, if not several months following a significant change in well water levels, are therefore believed to reflect the hydraulic conditions associated with the nearby fracture network, rather than those in the adjacent low-permeability matrix. Over time, water levels in the fractures will eventually equilibrate with those of the bedrock, but this process is likely very slow. The conceptual model is complicated by the possibility that infiltrating water may either fill empty fractures, draining directly into a screened interval, or it may simply displace water already present in the fracture network. This is relevant because under a “displaced water” scenario, water entering the well that is displaced from fractures by infiltration of surface water has already been present within the fracture network for a sufficient period of time to mix with local groundwater, and therefore might not show significant evidence of surface water chemistry.

In comparison to MW-1A and MW-1B, far less seasonal response is observed in MW-2A and MW-2B. Each shows a slight decline beginning in March 2012 and continuing until June 2012, a period that includes May redevelopment. MW-2A then rises approximately 39 feet back to a water-level elevation similar to that originally observed in late 2010. MW-2B only exhibits a modest rise of approximately 11 feet by December 2012. This suggests that the hydraulic connection between the seasonal influences that affect MW-2A, and the well screen in MW-2B is lower than in MW-2A and reflects limited effective vertical fracture communication between the two intervals.

Water levels in MW-3A are higher for each successive monitoring events between January 2011 and February 2012 (Figure 7). Water levels in MW-3A decline through June 2012 and stabilize at an elevation similar to that recorded in December 2010. MW-3B exhibits rises and declines in water levels with the same timing as observed in MW-3A, but with a much greater magnitude, rising approximately 300 feet between January 2011 and January 2012, where MW-3A only rises approximately 90-100 feet. The subsequent decline in water levels in MW-3B is similarly greater in magnitude, re-stabilizing at elevations similar to those observed in January 2011. The hydraulic connection between MW-3B and the seasonal influence, presumed to be related to seasonal snowmelt, is apparently much more pronounced than that of MW-3A, at least during peak snowmelt conditions. It is interesting to observe that the high water-level elevations in MW-3A and MW-3B are practically the same, further suggesting that the two share the same source as their influence during this time. However, neither water level is within 200 feet of the land surface elevation of the adjacent Divide Creek. This implies that the source of water may not be the creek, but some other snowmelt-fed fracture reservoir. The behavior of MW-3B water levels in which they rise abruptly seasonally, but do not recover after post-flood development, suggests that the connecting fracture reservoir may drain during non-flood conditions, becoming hydraulically disconnected from MW-3B.

During well-development events, efforts to purge these wells resulted in essentially complete evacuation of the well casing. The slow rate with which the recharge occurred indicates that during times of limited surface water, the Wasatch Formation itself may be limiting flow. During spring snowmelt, or following a significant precipitation event, infiltration may saturate fractures in the bedrock and rapidly increase water levels in wells. Under matrix recharge, the rate of transport of dissolved compounds would be likely be low, however during the surface-water recharge scenario, the well may fill rapidly as fractures saturate. Hydraulic loading from the surface may result in displacement of fluids already present in the fractures into the well, causing the well to fill without significantly changing the water chemistry.

Figure 10 and Table 3 provide an evaluation of the vertical gradient between the shallow and deep wells. With the exception of the nested wells at MW-3 during February and May 2012, the water-level elevation data from each of the groundwater monitoring events indicate a strong downward gradient at all three well nest locations. In February and May 2012, water-level elevations in MW-3A and MW-3B are within 5 feet of each other. This observation is believed to represent a seasonal condition associated with snowmelt events and/or surface water run-off, and therefore probably not representative of typical conditions. During the other water-level monitoring events, the observed water levels are fairly consistent, and show a consistent downward gradient. In the absence of further data, this conclusion is assumed to be a valid interpretation of local flow patterns, vertically.

5.3 Water Quality Characteristics

Page 6 of the Phase II Study Report (S.S. Papadopulos, 2008) notes:

> *"The water that is produced from Mesaverde Group gas wells normally has very high TDS concentrations relative to the water produced from alluvium and the Wasatch Formation. (The formation water is not as saline as ocean water and is considered to be brackish.) The transition in water quality from the Tertiary aquifer to the deeper hydrocarbon producing intervals in the Williams Fork Formation is not well understood in the study area because of a lack of water samples from the intervening area; but it is a potentially important factor in understanding the water quality relationship between the Wasatch and Williams Fork Formations."*

The employment of nested shallow and deep monitoring wells represents an attempt to provide further data to clarify the nature of the water quality relationship within the upper 600 feet of the Atwell Gulch Member of the Wasatch Formation.

5.3.1 Typical Shallow Water Quality in Wasatch Domestic Wells

Water quality data from domestic water wells in the Mamm Creek area was reviewed in the Phase I and Phase II study reports. Table 5-12 in the Phase I study report compares groundwater statistics for the water samples collected during the Phase I study and summarizes them. In domestic water wells, alkalinity was determined to have a mean concentration of 366.7 mg/L with a 156.7 mg/L standard deviation. Groundwater pH had a mean value of 7.79 with a standard deviation of 0.52. The mean concentration for chloride was 147.6 mg/L with a 316.6 mg/L standard deviation. Sodium concentrations averaged 310.5 mg/L with a standard deviation of 326.5 mg/L. TDS was determined to average 1,080.3 mg/L with a standard deviation of 845.3 mg/L. Sulfate concentrations averaged 353.8 mg/L with a standard deviation of 565.8 mg/L.

The Phase II study report focused on evaluating wells for which one or more compounds had previously been detected at concentrations above regulatory standards, or had Na-Cl concentrations that suggested possible mixing of shallow water with Na-Cl marine or brackish water. Additionally, water and gas samples were collected from gas wells in the vicinity for comparison. Table 4-1 of the Phase II study report summarizes the groundwater quality sample results from the investigation. A subset of the domestic wells that were located within a mile of the Phase III nested wells provides a summary of the shallow water quality around the investigation wells. The deepest domestic well for which a well depth was available was Well 703265 with a depth of 495 ft bgs. Groundwater samples collected from this subset of domestic wells had pH values ranging from 6.8 to 8.3. Sodium concentrations ranged from 30.8 to 1,150 mg/L. Bicarbonate as $CaCO_3$ concentrations ranged from 154 to 847 mg/L. Chloride concentrations ranged from 3.5 to 470 mg/L. Sulfate concentrations ranged from 17 to 2,070 mg/L. TDS concentrations ranged from 420 to 3,970 mg/L.

Dissolved methane concentrations in domestic well samples from 1997 to 2005 were summarized in the Phase I Study Report. The results for 2005 in Table 5.10 and indicate that during that year, the detected methane concentration range for Township 6S, Range 92W was 0.021 to 10 mg/L. For Township 7S, Range 92W the range of detected methane concentrations was 0.0008 to 20 mg/L.

Only two measurements of dissolved methane concentration were available for the subset of wells in the Phase II study report. The sample from domestic well 703983 contained a methane concentration of 3.93 mg/L and the sample from domestic well 704050 contained 0.0063 mg/L.

5.3.2 Typical Produced Water Quality

The Phase I Study Final Report (URS, 2006) states that produced water is generally high in TDS (10,000 to 20,000 mg/L), and the dominant water type is sodium chloride (Na-Cl). Dissolved gases within the Williams Fork Formation include thermogenic methane, specifically derived from the high temperatures associated with thermal cracking of oil and/or organic matter in sediments, a naturally occurring process that occurs when hydrocarbons are subjected to increased temperature underground.

The Phase II Study Report provided a summary of water quality data collected from 16 produced water samples in Table 4.3. pH values ranged from 6.4 to 8.2. Sodium concentrations had a range of 220 to 6,640 mg/L. Bicarbonate as $CaCO_3$ concentrations ranged from 142 to 6,110 mg/L. Chloride concentrations ranged from 311 to 11,800 mg/L. Sulfate concentrations were at or below laboratory detection limits. TDS concentrations ranged from 690 to 21,700 mg/L (at 180 deg).

5.4 Phase III Investigation Results

As noted in section 4.3.2, the sample results for MW-1B in January 2011 were above the MCL for benzene. Results of sampling events conducted in August and December of 2012 indicated that benzene concentrations subsequently declined to near or below the analytical detection limit, and below the MCL. The source of the benzene is not known.

Secondary drinking water standards listed in the Colorado BSGW are 400 mg/L for TDS (see Section 4.3.2) and 250 mg/L for chloride. All of the samples collected during 2011 and 2012 were greater than 400 mg/L for TDS. The high TDS is believed to be related in part to the development problems associated with these wells, and in part due to naturally occurring alkalinity, sulfate, and chloride in the groundwater. In the Currie Well samples, the TDS is probably due to a combination of naturally occurring bicarbonate, the naturally high concentration of sulfate, and presence of chloride. With the exception of the January 2011, August 2012 and December 2012 samples collected from MW-1A, all of the samples collected in 2011 and 2012 also were greater than the Colorado BSGW, secondary drinking water standard for chloride. The presence of elevated chloride at MW-1B relative to MW-1A most likely reflects increased flow or mixing of groundwater from deeper subsurface intervals with shallow groundwater supplies. During the two events in which samples were collected from MW-2B, chloride concentrations observed in MW-2A are higher than those in MW-2B, suggesting either a surface-derived source of chloride, or dilution of chloride at the depth interval of MW-2B. Natural sources of chloride include atmospheric deposition, and weathering of chloride-bearing minerals. Anthropogenic sources of chloride include de-icing salts, landfills, wastewater and water treatment facilities and agricultural practices. Chloride concentrations in MW-3A were initially higher than those in MW-3B in 2011 sampling, but declined to concentrations similar to that of MW-3B during 2012 sampling.

The results from the samples collected from the Currie Well show a gradual decline in sulfate concentrations from 2011 to 2012 and were above the Colorado basic standard for groundwater for sulfate (250 mg/L). Elevated sulfate concentrations in the general vicinity of the Currie Well have been documented in the Phase I and Phase II study reports, and are believed to be naturally occurring, or possibly related to agricultural practices in the area. MW-2A sampling results from both 2012 events contained sulfate in concentrations exceeding the Colorado basic standard for sulfate in groundwater as well. It was observed during sampling of both the Currie Well and MW-2A that the water possessed a sulfur-type odor. This implies an equilibrium involving sulfate and its reduced form, hydrogen sulfide, the source of the odor. In each case, pH and oxidation-reduction potential also suggest that sulfate may be reducing to hydrogen sulfide. All other samples collected from the Phase III nested wells contained sulfate concentrations below 250 mg/L. As noted earlier, water in the Currie Well may be influenced chemically by the water quality of the upgradient surface water impoundment. It is noted that the highest concentrations of sulfate and the only identified positive measurement of Total Coliforms, both possibly related to drainage of agricultural fields into the impoundment, were observed in samples collected from the Currie Well.

5.5 Groundwater Chemistry Characteristics

Evaluation of major inorganic chemistry can be helpful in identifying the sources and travel pathways of water in the subsurface vicinity of the installed well nests. For the purposes of evaluating water chemistry, Piper diagrams have commonly been used to present graphical representations of the dominant species for comparison with other samples. Piper diagrams are used to plot the chemistries for the various samples on a combination trilinear-type set of diagrams. The Phase I hydrogeologic characterization included discussion of the water chemistry associated with select groups of groundwater wells located in the vicinity of Rifle and Silt. The dominant cations are generally considered to include calcium, magnesium, sodium, and potassium. The dominant anions in typical environmental conditions include the carbonate species, bicarbonate and carbonate, chloride, and sulfate.

Water chemistry observed in the monitoring wells installed as part of this study were frequently found to possess pH values above 12, meaning that alkalinity as a laboratory measurement is largely dominated by the hydroxide ion and is unsuitable for plotting on the standard Piper diagram used to evaluate water chemistry in past studies. The pH criteria for inclusion in a comparative Piper diagram analysis (pH < 11.5 where acid neutralizing capacity is due in equal parts to the hydroxide ion and the carbonate ion) were met in the Currie well and the 2012 sampling results for MW-2A. Inorganic chemistry data for these samples have been plotted on a Piper diagram as provided in Figure 11. For the purposes of comparison, the Piper plots for the Phase II Study Report domestic well samples and the production well samples, representative of water composition in the Williams Fork Formation, are provided in Figures 12 and 13.

The water samples collected from MW-2A during 2012 contain a Na-Cl signature which plots in the same areas of the Piper diagram as many of the produced water samples, although it appears to contain more sulfate than in that of the produced water chemistry, suggesting that the well may represent a mix of typical shallow water with a higher concentration Na-Cl water source. The trilinear diagram for anion compositions shows that the proportion of chloride is higher than is consistent with shallow aquifer water.

The Currie Well water samples plot in an area of the Piper diagram with a Na-SO_4-Cl chemistry, a composition that is consistent with a high-sodium shallow aquifer water type.

5.6 Comparison of Phase III Well Chloride and TDS to Phase I and II Studies

The results of the Phase III well chloride observations are presented in Figure 9. Spatial distribution of chloride observed in wells within several miles of the Phase III investigation wells in the data set for 2004 and 2005 were compiled and are presented in Figure 14. Chloride data from December 2012 in the Phase III wells is also presented on Figure 14 for comparison. A time series plot of chloride concentrations in Phase III wells and other wells located within a 1-mile radius of the Phase III wells are presented on Figures 15a and 15b. Figure 15a presents data collected from 2004 to 2005 in the West Divide Creek seep area, and Figure 15b presents that same data along with the chloride data from the Phase III investigation wells.

Ambient chloride concentrations documented in the Phase I study report (URS, 2006) are usually less than 10 mg/L. Approximately 10 to 15 percent of the samples from domestic wells in the Phase I study report were contained concentrations of chloride above the Colorado BSGW, secondary drinking water standard of 250 mg/L. The mean concentration of chloride in domestic wells reported in the Phase I study report was 148 mg/L.

The mean chloride concentration from sampled domestic wells as documented in the Phase II study report (S.S. Papadopulos, 2008) was 166 mg/L. Approximately 15 percent of the samples from domestic wells in the Phase II study report contained concentrations of chloride above the Colorado BSGW, secondary drinking water standard of 250 mg/. The mean chloride concentration from produced water sampled and documented in the Phase II study report (S.S. Papadopulos, 2008) was 5,765 mg/L. All samples from the produced water in the Phase II study report chloride exceeded the Colorado BSGW, secondary drinking water standard of 250 mg/.

In general, chloride concentrations are higher in Phase III wells MW-1B, MW-3A and MW-3B than concentrations observed in the domestic well samples from the Phase I and Phase II studies in 2004 and 2005. The elevated concentrations are believed to reflect the greater depth of the Phase III investigation wells, as compared to the depths of the domestic wells sampled in the Phase I and II studies. A discussion of the possible sources of the chloride is presented later in Section 6.

TDS concentrations documented in the Phase I study report (URS, 2006) ranged from less than 1,000 to nearly 6,000 mg/L, with a mean of 1,074 mg/L. As noted in Section 4.3, the Colorado BSGW, secondary drinking water standard for TDS is based on a sliding scale, and a concentration of 400 mg/L was used as a reference standard for TDS in this report. Approximately 88 percent of the samples from domestic wells in the Phase I Study Report were found to contain concentrations of TDS above 400 mg/L. The mean concentration of TDS in domestic wells reported in the Phase I Study Report was 1,080 mg/L.

TDS concentrations in domestic wells as documented in the Phase II study report (S.S. Papadopulos, 2008) ranged from 350 to 10,100 mg/L with a mean of 1,518 mg/L. Approximately 95 percent of the samples from domestic wells in the Phase II study report contained concentrations of TDS above 400 mg/. The mean TDS concentration from produced water sampled and documented in the Phase II study report (S.S. Papadopulos, 2008) was 12,566 mg/L. All samples from the produced water in the Phase II study report TDS were greater than 400 mg/L.

In general, TDS concentrations are higher in Phase III wells than concentrations observed in the domestic well samples from the Phase I and II studies from 2004 and 2005. As noted in Section 4.3.4, TDS in the Phase III nested wells is generally considered to be influenced by grout-intrusion into fractures during well construction, and is of limited usefulness for comparison to other data sources. However, the Phase I study noted higher TDS is generally present in the eastern portion of the study area where the Phase III wells are located. The Phase I study report also generally found that lower TDS water was present along stream drainages, but that Dry Hollow Creek (which flows immediately to the west of the Currie Well) is an exception to this, containing elevated TDS concentrations.

5.7 Dissolved Methane Analyses

Dissolved methane concentrations observed in the Phase III wells during 2011 and 2012 are presented as a time series plot on Figure 17.

In Well Nest 1, the May 2011 concentrations of methane increase with depth from 13 mg/L in MW-1A to 36 mg/L in MW-1B. These concentrations are higher than those detected in either the Phase I or Phase II Study Reports and indicate the presence of an elevated concentration source of methane. In 2012, the concentrations of methane in both of the nested wells declined to under 6 mg/L in August, then increased to 8.9 mg/L (MW-1A) and 8.7 mg/L (MW-1B) in December.

Figure 8 shows dissolved methane concentrations for samples collected during the Phase III investigation.

In Well Nest 2, the concentrations of methane decrease with depth. Methane concentrations in MW-2A range from 66 mg/L (May 2011) to 140 mg/L (August 2012). Methane concentrations in MW-2B range from 22 mg/L (January 2011) to 12 mg/L in MW-2B (May 2011). Water quality samples could not be collected from MW-2B during either of the two 2012 sampling events. The concentrations in MW-2A represent the highest concentrations of methane detected in the group of installed well nests.

In Well Nest 3, the concentrations of methane consistently decrease with depth between MW-3A and MW-3B. Dissolved methane concentrations in MW-3A range from 5.9 mg/L (January 2011) to 13 mg/L (January 2013). In samples collected from MW-3B, methane concentrations range from 0.36 mg/L (January 2011) to 2.3 mg/L (December 2012). Decreasing concentrations with depth suggests the presence of a shallow source of methane, or depletion of methane from depth. Given that no likely source of methane appears present in the soils between 400 ft bgs and land surface at either Well Nest 2 or 3, the likely cause of the concentration gradient is gas flow through shallow fracture sets that intersect the boreholes at a depth near or above 400 ft bgs at these locations.

5.8 Comparison of Phase III Well Dissolved Methane to Other Study Data

Spatial distribution of methane observed in wells within several miles of the Phase III wells as compiled in the various other historical data sets (Phase I Hydrogeologic Study, Phase II Hydrogeologic Study, and West Divide Creek Seep Study) are presented in Figure 16. Methane data from December 2012 in the Phase III wells is also presented on Figure 16 for comparison. A time-series plot of dissolved methane concentrations during 2011 and 2012 for the Phase III wells is presented in Figure 17. A time-series plot of dissolved methane concentrations reported in the Phase I report along-side the data collected during 2011 and 2012 for the Phase III wells is presented in Figure 18. In general, methane concentrations observed in the Phase III wells are similar to those observed in surrounding wells in 2004 and 2005. An exception is MW-2A in which elevated methane concentrations have been measured within a range from 66 to 140 mg/L (Figure 17). The highest concentration of methane observed in any of the other Phase III wells was 13 mg/L in MW-3A.

Although it is possible that the source of the elevated methane concentrations observed in MW-2A is related to an artificial and localized source of methane, it is also possible that these measurements represent anomalously high concentrations of naturally occurring methane. The nature of the unfractured parts of the Wasatch Formation, consisting of lenses of more permeable sandstone encapsulated in lower permeability siltstones may lend itself to the occurrence of localized, and likely isolated pockets of methane. Although there are not coal beds or evidence of coal-bed methane documented as originating in the Wasatch Formation in the Phase I

Investigation, the Sandstone Unit of the overlying Shire member of the Wasatch Formation (identified as the Wasatch "G" of Carlstrom, 2003) produces natural gas in the Parachute and Piceance Creek Fields. It is therefore likely that naturally occurring pockets of elevated methane content persist in the upper sections of the Atwell Gulch member. The isotopic signature of the methane observed in each of the Phase III wells is discussed in the following Section 5.9 as a diagnostic.

MW-1A and MW-1B are located within one mile of the West Divide Creek seep area. Methane concentrations in these two wells were observed in a range between 5.7 and 13 mg/L in MW-1A and between 3 and 36 mg/L in MW-1B. To evaluate the potential for further migration of methane associated with the seep area source, a time-series plot of methane for a set of the West Divide Creek seep study wells is presented in Figure 18 along with methane concentrations observed in MW-1A and MW-1B. While concentrations in the seep area wells decline over time to concentrations similar to those found in the nested well MW-1 in December 2012, the methane concentrations observed, particularly in MW-1B exceed those found in the seep area wells in 2011. This suggests that there may be an alternate source of methane that causes the temporarily elevated 2011 methane in MW-1B.

5.9 Gas Composition and Methane Stable Isotopes in Groundwater

The stable isotopes of carbon ($\delta^{13}C_1$) and hydrogen (deuterium; δDC_1) have been used in various studies to help identify the source of dissolved methane in water samples. Methane formed at higher temperatures (> 160 degrees C) associated with the thermal cracking of oil and/or solid organic matter contains a higher ratio of ^{13}C to ^{12}C, or isotopically heavier carbon (thermogenic methane). Methane formed at lower temperatures due to the decomposition of organic matter by anaerobic bacteria under near surface, low-temperature conditions tends to contain isotopically lighter carbon, or a lower ratio of ^{13}C to ^{12}C (biogenic methane). Thermogenic methane also tends to be relatively enriched with respect to the hydrogen isotope of deuterium (elevated δDC_1values), compared to that observed with biogenic methane. Methane associated with gas production in the Piceance basin in Garfield County is believed to be predominantly thermogenic gas (Johnson and Rice, 1990).

In his Review of Phase II Hydrogeologic Study, Dr. Geoffrey Thyne investigates different pathways by which different isotopic compositions of methane may form. One possibility includes that microbial carbonate-reduction pathway may occur in which the acetate molecule is converted to CO_2 then reduced to CH_4, in addition to the microbial reduction of the natural organic matter noted above (Botz et al. 1996). During this process, the carbon isotopic value of the resulting methane becomes depleted relative to the parent CO_2. Dr. Thyne suggests that methane associated with this biogenic carbonate reduction may actually be derived from the thermogenic CO_2 coming from the Williams Fork Formation and may therefore be considered thermogenic. Dr. Thyne's final report references a study by Scott et al. (1994) which suggests that the methane produced by the reduction of Williams Fork CO_2 gas would have a $\delta^{13}C_1$ value of -76 ‰ similar to what was observed in the Phase II study.

An alternative interpretation for the thermogenic isotopic signatures is that the methane was originally biogenic fermentation gas and has been oxidized by microbial processes (CH_4 to CO_2), a process which preferentially selects for the lighter carbon over the heavier carbon, creating CO_2 with a relatively depleted $\delta^{13}C_1$ value, while leaving an enriched "residual" methane that appears to be thermogenic (S.S. Papadopulos, 2008).

As noted in the Phase II Hydrogeologic Report, an additional tool that can be brought to bear on the problem is the consideration of the heavier hydrocarbons associated with thermogenic gas formation. Methane is not the only gas which may be produced through the cracking process. Natural gas typically consists of one to four carbon (C_1 to C_4) organic molecules as well as numerous hydrocarbons consisting of greater than 4 carbon molecules. Multiple processes can create methane, including thermogenic processes and biogenic processes associated with shallow bacteria that generate "swamp gas." However, biogenic gas is "dry", limited almost entirely to the single-carbon organic hydrocarbons, and mostly lacking the higher molecular weight "wet" organic molecules C_2 to C_4 as well as the even higher molecular weight (C_5+) "condensate" molecules (GasChem, 2011). By using Bernard diagrams, in which $\delta^{13}C_1$ is plotted against the hydrocarbon gas ratio $C_1/(C_2+C_3)$, the source of the methane gas may become more evident (Whiticar, 1990; based on Bernard et al., 1978). Because the heavier hydrocarbons, or wet gases (C_2 and C_3 and heavier), are not readily formed by microbial activity, the presence of heavier hydrocarbons suggests a thermogenic or a mixed methane source.

Isotopic and wet-gas chemistry analysis was performed on dissolved methane for each of the samples collected during the 2011 and 2012 sampling events, with the exception of the sample from MW-1B from August 2012 which did not contain sufficient methane concentrations to allow isotopic analysis. The results of the January 2011 isotope analyses are presented in Figure 19a. The Bernard diagram for the January 2011 analyses is presented in Figure 19b. The results of the May 2011 isotope analyses are presented in Figure 20a. The Bernard diagram for the May 2011 analyses is presented in Figure 20b. The results of the August 2012 isotope analyses are presented in Figure 21a. The Bernard diagram for the August 2012 analyses is presented in Figure 21b. The results of the December 2012 isotope analyses are presented in Figure 22a. The Bernard diagram for the December 2012 analyses is presented in Figure 22b.

The $\delta^{13}C_1$ versus δDC_1 isotope plots (Figures 19a, 20a, 21a, and 22a) suggest that the methane observed in MW-1B and MW-2B is thermogenic in origin. The Currie Well seems likely to represent a biogenic methane source derived from CO_2 reduction. This conclusion is confirmed by the Bernard diagrams (Figures 19b, 20b, 21b, and 22b). The source of the methane in the other four wells is less clear. At least the two different pathways identified above are considerations for the source of the methane in these samples. The presence of wet-gas molecules in the samples collected from MW-1A and the isotopic signature of MW-1A samples suggest that the methane may be due to a mix of sources. Wet-gas content and isotopic signature in the January 2011 sample from MW-3B indicate a thermogenic source; however, in May 2011, the same indicators suggest a biogenic or mixed-methane source. August and December 2012 samples collected from MW-3B indicate that methane source signature begins to shift back toward a predominately thermogenic source.

The samples collected from wells MW-2A and MW-3A plot within or on the edge of the biogenic methane zone on the Bernard diagrams (Figures 19b, 20b, 21b, and 22b), suggesting that methane in these wells is likely to be biogenic in origin.

The apparent isotopic signature for Well Nest 1 is consistent with a thermogenic source for the deeper methane well (MW-1B), and a mixed thermogenic/biogenic, or potentially reduced thermogenic methane source for MW-1A. The isotopic signature for the source of methane in Well Nest 3 is consistent with that of a surface source of biogenic methane with mixed thermogenic/biogenic source of methane in MW-3B, likely changing temporally. The source of methane in samples collected from Well Nest 2 is unclear. MW-2B appears to be thermogenic in origin, but the methane signature associated with MW-2A appears to be biogenic, generated through CO_2 reduction.

5.10 Comparison of Phase III Well Methane Isotopes to West Divide Creek Seep Study Data

As noted previously, the methane observed in the West Divide Creek seep was believed to have originated from gas production well Schwartz 2-15B. The isotopic signature for water samples collected from a set of domestic and monitoring wells associated with the investigation of the West Divide Creek Seep Study in 2005 is presented in Figure 23. Using symbol colors based on the isotopic methane-source interpretation for each well, a map of the wells is presented in Figure 24. The monitoring wells along West Divide Creek near the seep generally plot in the thermogenic range with the exception of MW19, a monitoring well located in a marshy area which plots in the biogenic fermentation zone, and MW23 and the Schwartz monitoring well for which the signatures appear to be due to carbonate reduction. Samples collected from the domestic water wells in the area generally plot in the biogenic carbonate reduction range with the exception of the Spaulding Water Well and Dietrich Water Wells whose isotopic signatures suggest a mixed-source origin for the methane.

The isotopic signature for water samples from the domestic wells sampled as part of the as part of the West Divide Creek Seep Study (Figure 23) are generally similar to the isotopic signature of the shallow Phase III wells in that they appear to have primarily a biogenic carbonate-reduction methane source. However, while methane in the shallow Phase III wells is likely to be primarily biogenic in origin, the presence of wet-gas molecules and/or the isotopic signatures suggest that the methane may also be partially mixed with gas from a thermogenic source. As noted above, the isotopic signatures for the Spaulding Water Well and Dietrich Water Wells also suggest a potentially mixed biogenic and thermogenic source for methane.

With the exception of monitoring wells MW19 and MW23 and the Schwartz monitoring well noted above, the monitoring wells installed as part of the West Divide Creek Seep Study generally suggest a thermogenic range. Initially, the isotopic signatures for all three of the deeper Phase III monitoring wells were similar to those of the West Divide Creek Seep Study monitoring wells. The data from MW-1B then indicated a shift towards a biogenic source followed by a mixed-methane source.

5.11 Other Detected Organic Compounds

Several volatile organic compounds whose origins are unknown were detected in samples collected from the wells. Acetone was detected in each of the samples collected from the nested wells during the investigation. Chloroform was detected in samples collected from MW-2A and MW-3A. 2hexanone, and methyl-ethyl ketone (2-butanone) were detected in samples collected from MW-2B and MW-3B, and 2-hexanone was also detected in MW-3A. Of note, acetone and methyl-ethyl-ketone (2-butanone) are volatile organic compounds commonly observed as laboratory contaminants (USEPA, 1999).

Benzene is a volatile organic compound with an EPA MCL of 5 ug/L. In groundwater, benzene is typically associated with gasoline or other petroleum releases to the environment, however it can also occur in some natural gas reservoirs (Thomas and McMahon, 2012). Benzene was detected in samples from MW-1B, MW-2B, MW-3B, and the Currie well. The benzene concentration in MW-1B in the January 2011 water sample (5.3 µg/L) exceeded the MCL standard (5 µg/L). Elevated concentrations in subsequent sample events were not observed, however. Samples collected from MW-1B in August and December 2012 contained benzene concentrations less than the MCL at concentrations of < 1.0 and 1.3 µg/L, respectively. Benzene was detected in the January 2011 sample collected in MW-2B at a concentration of 3.9 µg/L, but was lower, 1.4 µg/L, in the May 2011 sample. Benzene was detected in the January 2011 sample collected in MW-3B at 1.2 µg/L, but was not detected in concentrations above the laboratory detection limit in samples collected in May 2011 or August 2012. Benzene was then detected again at 1.5 µg/L in the December 2012 sample in MW-3B. Benzene has been detected in the Currie well at concentrations between 1 and 2 µg/L in each of the four sampling events.

As noted in previous studies, benzene has sporadically been found in water samples collected from wells in the Wasatch Formation around the Mamm Creek – Divide Creek Area, typically in concentrations below the MCL. The fluctuations in benzene concentrations are likely due to natural variation. With the exception of the Currie Well, all of the wells in which benzene has been detected have been the B-zone wells. It seems likely that the source of the benzene is deeper than the B-zone (~600 feet bgs), and that the fluctuations in benzene concentrations are due to natural variation. As the benzene concentrations have been found in each of the three

Phase III well nests at low concentrations, the source of the benzene at depth is probably widespread, rather than localized. This suggests that the benzene ultimately is present naturally throughout the Wasatch Formation, and perhaps influencing groundwater in the Mamm Creek – Divide Creek Area due to the structural fracture network associated with the anticline.

5.12 Quality Assurance and Quality Control

The procedures and protocols from the project QAPP (GeoTrans, 2011) were used in sample collection, sample shipping and custody transfer, and data generation to the extent possible. The primary deviation from the QAPP occurred during low-flow sampling. The project QAPP goal is to achieve a steady flow rate while maintaining a drawdown of less than 0.33 feet, but also notes that the goal of a drawdown of less than 0.33 feet may be difficult to achieve due to some geologic heterogeneities and may require adjustment based on site-specific conditions. In most cases, the drawdown during low-flow sampling of the Phase III wells was greater than 0.33 feet due to low formation permeability and the use of small screen intervals to collect samples from discrete depth intervals. However, prior to sampling, indicator field parameters for all samples were stabilized to within the limits specified in the QAPP and EPA-accepted protocols indicating collection of representative groundwater samples with one exception. The turbidity readings from MW-2A in May 2011 exceeded the QAPP-specified variance of 10%. The final three turbidity readings were 3.82, 3.68, and 4.65 Nephelometric Turbidity Units (NTUs). However, these turbidity values met EPA-accepted criteria that three consecutive turbidity readings below 5 NTU are considered stabilized.

Field equipment was calibrated prior to the start of each sampling day according to the manufacturer's guidelines. The multi-parameter probe and flow through cell used to collect field water quality parameters was rinsed with distilled water prior to each use. In addition to the investigative samples collected during this investigation, QA/QC samples were collected in accordance with the QAPP. These consisted of field duplicate samples and trip blanks. Additional laboratory internal quality checks were performed and the results are included in the laboratory analysis reporting documentation.

During each of the four water quality sample collection events, a field duplicate sample was collected for analysis of hydrocarbons and general chemistry parameters. In January 2011, a duplicate sample was collected from MW-1B, in May 2011, a duplicate sample was collected from MW-2A, and in August and December 2012, duplicate samples were collected from MW-1A. The samples were collected by alternately filling the primary sample bottle and the duplicate sample bottle. These samples were then submitted as blind samples to serve as validation of laboratory analytical processes. The relative percent difference (RPD), a measure of the agreement or reproducibility among replicate measurements, was calculated for the samples using the following equation:

$$\mathrm{RPD} = 2 * \frac{\mathrm{D1} - \mathrm{D2}}{\mathrm{D1} + \mathrm{D2}} * 100$$

Where:

RPD = Relative percent difference;
D1 = First sample value; and
D2 = Second sample value (duplicate sample).

The project-specific RPD control limit was ±30%. Of the four duplicate samples collected, only one parameter did not meet the ±30% control criteria. The RPD for benzene in the parent and duplicate sample from MW-1B in May 2011 was 31.4%. Given the RPD only exceeded the control limit by 1.4% and the RPDs for the remainder of the data fell within control limits, no corrective actions were recommended.

Trip blanks, or samples of water obtained from the analytical laboratory, were transported along with the investigative samples to confirm that no external contamination of volatile organic compounds occurred during transit. There were no analytes detected in the trip blank samples.

As noted in Section 3.6, development water obtained from the Town of Silt municipal water supply was used during the second of the two 2012 well development events in an attempt to improve well conditions by mobilizing and removing the high pH fluid in the surrounding fracture network. Two samples were collected from the Silt municipal water source for laboratory analysis. The laboratory reports are provided in Appendix C. The laboratory results showed no detections of analyzed organic constituents and on average the municipal water contained lower concentrations of inorganic constituents. The wells were purged following the addition of the municipal water to remove the water and mobilized grout materials. Evaluation of results from subsequent monitoring events indicated the addition of the municipal water did not impact these results.

6.0 DISCUSSION

The challenge of evaluating the possible effects of oil and gas development on the Wasatch Formation water quality is a complex undertaking. Reliable conclusions require that background chemistry of the groundwater is established before local drilling operations occur, so that clear indication of changed conditions can be confirmed after drilling. Ambient groundwater chemistry conditions pre-dating natural-gas exploration and production in the area is poorly defined spatially, and virtually unevaluated with respect to depths below 400 ft bgs. The area in the immediate vicinity of the investigation wells includes an area characterized by its alignment with the axis of a plunging anticlinal structure, and the related high-angle fracturing present as a result. Drilling complications associated with these structural features have led to the establishment of the Mamm Creek Special Drilling Zone, in which restrictions on the methods used to drill and construct natural-gas production wells have been implemented. Natural gas formed thousands of feet deep below land surface and pressurized gases and fluids may have been continuously escaping to the surface over time through these naturally occurring fractures, causing localized impacts to groundwater in the Wasatch Formation.

Three sets of nested monitoring wells were installed within the Wasatch Formation in the Mamm Creek Study Area, located south of Silt in Garfield County, Colorado. Each well nest was drilled using air-rotary techniques and completed as a pair of nested wells screened at approximately 400 and 600 feet bgs. Each well was developed by air-lifting following well completion, and subsequently redeveloped twice due to suspected cement-grout intrusion into fractures around the wells.

Potentiometric Interpretation

Water levels measured in the three sets of nested wells demonstrate evidence of a dual-porosity bedrock groundwater conceptual framework. It is likely that none of the water level measurement events represents a true measure of static potentiometric conditions at the location. Following drilling, the initial water levels may still have been responding to the localized impacts of well development following well installation. Later water level measurements may have been affected either by further well development activities or by surface water infiltration into the fractures that influence the observed water levels at the well. If water levels require a significant amount of time (> 6 months?) to reach equilibrium with the low-permeability siltstones of the Wasatch, particularly in the deeper completion intervals, then even the apparent consistency of the downward gradients observed and interpreted in Figure 10 may not reflect long-term static conditions. Caution should therefore be taken when trying to interpret whether water levels in the wells reflect upward or downward movement of groundwater at the location.

Using the data collected during this investigation, and assuming that at least the water levels measured during late-2012 and early-2013 reflect an approximate equilibrium with static conditions, the tentative interpretation of downward flow at each of the three well sets is believed to be correct.

Inorganic Chemistry

While alkalinity, TDS and pH values are believed to have been artificially impacted by chemical reactions associated with grout intrusion into fractures around the well bores, methane concentrations and isotopic ratios are believed to remain reliable water quality measures for this study. All six of the wells in the nested pairs initially contained high pH water. However, the methane isotopic data from each well has remained relatively consistent over time, therefore the usefulness of the isotopic signature tool for determination of the source of dissolved methane in a sample appears unaffected by grout induced chemical reactions near the well bores.

Analysis of inorganic constituents for the groundwater samples generally reflects chemistry with sodium, chloride, and TDS concentrations that would be expected for wells completed in deeper aquifer zones. Shallower wells would be expected to have lower concentrations of these constituents due to dilution from surface recharge influences. Surface water samples from West Divide Creek as part of the seep study contained chloride concentrations in the range of approximately 10 to 50 mg/L and TDS concentrations in the range of approximately 350 to 600 mg/L. With the exception of MW-2B, which was not sampled in 2012 because water levels were below the maximum pump capacity, chloride concentrations are higher in the B-zone wells than in the A-zone wells or in the Currie Well. Elevated concentrations with depth indicate that the source of the chloride is likely deeper than the B-zone wells and that a concentration gradient between the source at-depth and the more dilute waters nearer the surface exists. The chloride source may be an interval of the Wasatch Formation itself, or it may be from the Williams Fork Formation stratigraphically below the Wasatch Formation. Figure 14 illustrates the concentration of chloride within water wells in the Mamm Creek-Divide Creek Area. The spatial distribution does not indicate a significant grouping of higher or lower concentrations of chloride, suggesting that the source is relatively consistent throughout the area. Additionally, the variability in well depths likely influences the observed chloride concentrations, complicating spatial interpretation. Based on the data collected in this study, it is unclear whether the Wasatch Formation or the Williams Fork Formation is the ultimate source of the higher sodium, chloride, and TDS concentrations.

Benzene

The benzene concentration in MW-1B in the January 2011 water sample (5.3 µg/L) was found to be above the MCL standard (5 µg/L). This elevated concentration was not observed subsequent sampling events. Samples collected from MW-1B in August and December 2012 contained concentrations less than the MCL of < 1.0 and 1.3 mg/L, respectively. Benzene was detected in MW-2B at concentrations of 3.4 and 1.4 µg/L during the January 2011 and May 2011 sampling events. Analysis of samples for benzene collected from MW-1A, MW-2A, and MW-3A generally indicated low concentrations at or below the detection limit. MW-3B and the Currie

Well contained concentrations of benzene that ranged from non-detect (< 1 µg/L) to 1.5 µg/L (MW-3B) and from 1.3 to 1.8 µg/L (Currie Well).

Variation in benzene concentrations in each of the wells is believed to be the result of natural variation. The initially high concentration of benzene observed in MW-1B is likely to be anomalous, perhaps related to the installation of the well in a previously isolated lens containing benzene.

Methane and Isotopic Methane Signatures

Dissolved methane concentrations of greater than 1 mg/L, were found in each of the Phase III investigation wells. Of these wells, the Currie Well and MW-3B contained less than 10 mg/L, and the rest contained methane concentrations in excess of 10 mg/L. In Well Nest 1 (MW-1A, MW-1B) methane concentrations were higher in the deeper well than the shallower well during the January 2011 and May 2011 sampling events. However concentrations in MW-1B declined after the May 2011 sampling event and concentrations were higher in the shallow wells during the August 2012 and December 2012 sampling events. In both Well Nest 2 and Well Nest 3, methane concentrations were higher in the shallow well than the deeper well.

Applying the conceptual model of groundwater behavior to methane, shallow methane dissolved in groundwater is present at the location of the MW-1A screened interval but exhibits the effects of dilution during the August 2012 sampling event. The cause of the decrease in methane concentrations in MW-1B may be similar to that of benzene during the same time period in which a water-level rise, believed to be associated with infiltration of surface water, apparently caused dilution of measured concentrations. Methane concentrations in MW-2A appear anomalous in the context of this study, suggesting that something different is occurring at the location and specific depth interval. Finally, methane is observed to be present in the ambient groundwater at the MW-3A screen interval at similar concentrations to those at MW-1A. MW-3B contains consistently low (< 4 mg/L) concentrations of dissolved methane.

Carbon and hydrogen isotopic analysis of dissolved methane suggest a thermogenic source in MW-1B and MW-2B. Biogenic reduction of CO_2 is believed to be the source of methane in the Currie Well, MW-2A and MW-3A. The source(s) of methane in MW-1A and MW-3B are unclear. The results from MW-1A may possibly represent either a biogenic source, a mix of biogenic and thermogenic sources, or an intermediate step in isotopic fractionation between the two zones on the isotopic diagrams (Figures 19a, 20a, 21a, and 22a). Isotopic analyses of the samples collected from MW-3B during the January 2011, August 2012 and December 2012 events appear to represent a thermogenic source, however the corresponding isotopic analysis from the May 2011 event may represent either a mix of biogenic and thermogenic sources, or an intermediate step in isotopic fractionation between the two zones on the isotopic diagrams. Methane concentrations measured during each of the sampling events are presented in Figure 17 and the isotopic source interpretation for these samples as discussed above are illustrated in Figures 19a, 20a, 21a, and 22a.

Wet-gas ($C_2 – C_4$) dissolved in a water sample can be a good indication of the volatile organic source of gases such as methane. As discussed in detail in Section 5.9 earlier, although short-chain organic compounds such as the one-carbon methane molecule can be produced as the result of shallow biogenic activity, longer carbon-chain organic molecules such as ethane, propane and butane (2-, 3-, and 4-carbon molecules) are not commonly produced in these environments. Elevated concentrations of wet-gas constituents therefore tend to indicate a genesis environment compatible with the development of complex organic compounds. Concentrations of wet-gas components are typically evaluated using a ratio of one-carbon molecules to the sum of two- and three-carbon molecules: $C_1 / (C_2+C_3)$. A Bernard diagram plots the $\delta_{13}C$ for dissolved methane on the x-axis against this wet-gas ratio. Dissolved gases with a wet-gas ratio above 550 are consistent with a biogenic-type genesis, where those with a ration below 65 are consistent with a thermogenic genesis.

Wet-gas ($C_2 – C_4$) analyses using a Bernard diagram suggest that the methane present in MW-1B and MW-2B has a thermogenic source. In each case, the wet-gas ratio is below 65 and has a methane $\delta_{13}C$ consistent with this interpretation. Chemical composition of water samples collected from MW-1A and MW-3B contain wet-gas chemistry (a ratio between 65 and 550) that implies possible mixing contributions of thermogenic gas. Low concentrations of wet-gas components were detected in samples collected from MW-2A and MW-3A, with concentration percentages typically less than 0.1 percent. The source of these components is unclear. Analysis of the samples collected from the Currie well suggests a biogenic source, lacking significant concentrations of wet-gas constituents. Bernard diagrams supporting the wet-gas interpretations for samples collected from each of the four groundwater sampling events as discussed above are illustrated in Figures 19b, 20b, 21b, and 22b.

7.0 SUMMARY OF FINDINGS

The objective of the Phase III Hydrogeologic Characterization of the Mamm Creek Area was to gather additional data to clarify the nature of the hydrologic flow system and water quality in the study area, including evaluating the possible effects, if any, of oil and gas development on the Wasatch Formation water quality. Three sets of nested groundwater monitoring wells were installed to facilitate collection of data for the evaluation of three-dimensional hydrologic flow system and water quality in the Mamm Creek study area to assist in achieving these objectives. Multiple constituents were evaluated in the analysis of samples collected from these wells, with specific focus on analytes believed to represent compounds of interest. These include chloride, methane and benzene. Each compound was detected in wells sampled during this Phase III investigation.

Generally speaking, the dissolved methane observed in Phase III shallow wells (< 400 feet deep) in the study area appears to have a biogenic carbonate-reduction source, based on the carbon and hydrogen isotopic analysis. A biogenic carbonate-reduction source implies that the methane does not originate from a deep source or from natural-gas operations, instead representing the reduction of carbon dioxide gas to methane. This is consistent with observations from each of the three sets of nested wells in which each of MW-1A, MW-2A and MW-3A, as well as the Currie well, all of which appear to be either biogenic carbonate-reduction in source, or mixed biogenic-thermogenic in the case of MW-1A. In each round of groundwater sampling, the dissolved methane observed in the MW-1B and MW-2B has isotopic signatures indicating a thermogenic origin. The dissolved methane in MW-3B initially had an isotopic signature consistent with a thermogenic source in January 2011, but the signature changed to that of a biogenic source in May 2011 before shifting back towards a signature more consistent with a mix of biogenic and thermogenic sources and a thermogenic source in August and December 2012. Methane concentrations observed in deeper wells have exhibited a constant or declining trend between 2011 and 2012. This apparent trend is believed to be caused by dissipation of isolated pockets of native methane intercepted during well installation. Methane concentrations observed in 2012 are believed to be most representative of shallow aquifer concentrations. In samples collected during 2012, the highest observed concentration of dissolved thermogenic methane was 8.7 mg/L in MW-1B and the lowest concentration was 0.53 mg/L in MW-3B.

Bacteria (acetogenic, fermenting, and methanogenic) necessary to perform the carbonate-reduction reactions may be present in the upper 400 feet of the low-permeability siltstones around the nested wells, but are either not present at greater depth, or one of the other requirements of the reaction pathway (such as the availability of acetate) is not present. Groundwater present in the wells screened in the upper 400 feet generally show reducing conditions (low dissolved oxygen, low redox measurements, observations of the smell of hydrogen sulfide in shallow wells). Since oxidation of thermogenic methane to CO_2 would lead to additional fractionation, shifting the isotopic composition of the remaining methane further into the thermogenic zone, it seems unlikely that the thermogenic methane observed deeper is the source material from which the shallow biogenic methane is derived.

Dissolved methane concentrations in MW-1A and MW-1B generally exhibit declining concentrations over time as observed during the four groundwater sample collection events. During this time, both the isotopic signature of the methane in MW-1A and the wet-gas analysis continue to appear to represent a mix of biogenic carbonate reduction and thermogenic methane. The isotopic and wet-gas analysis signatures for MW-1B suggest a thermogenic origin for the methane observed at the deeper screen interval. Initially elevated concentrations may be related to the deeper well screen intersecting lenses of stratigraphy in which methane has accumulated in the Wasatch Formation over time. With less influence from near-surface seasonal dilution of waters, the methane concentrations are slightly higher than those observed at a shallower depth. High concentrations of dissolved methane do not necessarily imply impact from nearby gas production activities. The highest observed concentrations of methane were found in MW-2A with a range between 66 and 140 mg/L. The isotopic and wet-gas interpretation of the source of the methane remains within the biogenic (carbonate-reduction) zonations, suggesting that the methane was formed naturally within the shallow subsurface by bacterial processes.

Benzene concentrations in MW-1A and MW-1B also generally exhibit declining concentrations over time as observed during the four groundwater sample collection events. Based on observations of benzene concentrations observed in the investigation wells, low concentrations of benzene are likely present throughout the area due to some combination of natural migration from the deeper Williams Fork Formation and naturally occurring benzene in the Wasatch Formation. Below 400 feet, concentrations of benzene may be observed to be higher with increasing depth due to naturally higher benzene at depth.

Chloride concentrations observed in the Phase III wells MW-1A, MW-2A, MW-2B and the Currie Well are generally consistent with those observed in other domestic wells in their vicinity that were sampled as part of the Phase II study. Concentrations of chloride observed in MW-1B, MW-3A and MW-3B are somewhat higher than those observed in the surrounding wells. Concentrations of chloride are also typically higher in the vicinity of the Divide Creek Anticline, ranging from several hundred mg/L to nearly 2,000 mg/L in other wells. Since the Williams Fork Formation underlies the Wasatch Formation, the anticline structure and related fractures may provide the means for transport of fluids from the deeper and higher salinity zones to the surface in the area.

8.0 RECOMMENDATIONS

The monitoring wells may be useful to obtain future water-level measurements or water-quality data. Although it appears that cement-grout used during well construction may be affecting groundwater chemistry in terms of elevated pH, the impacts of the cement-grout are expected to dissipate with time. In addition, the observed dissolved gas concentrations are believed to be representative, and the various chemical parameters monitored as part of this investigation are believed to be representative of local groundwater chemistry. Therefore, additional development efforts are not believed to be necessary. The wells have provided water-level and water-quality data representative of the 2011 to 2012 timeframe, and if warranted in the future, can be utilized for collection of water quality samples for comparison to those collected as part of this investigation. Should additional samples be collected, the limited water production of the wells requires appropriate planning and implementation to ensure representative water samples are collected.

If future studies, designed to characterize water quality at depths similar to this study, are contemplated, consideration to the probable limited water production should be accounted for in well design, planned development activities, and groundwater sampling techniques. The wells may not yield the typical volumes of water removed during development without extensive efforts, and limited yield may impact sampling protocols. Deeper wells may also result in greater depths to water, requiring appropriately sized sampling pumps to achieve the required lift.

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