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PAVILLION, WYOMING AREA DOMESTIC WATER WELLS DRAFT FINAL REPORT AND PALATABILITY STUDY

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LIST OF ACRONYMS AND ABBREVIATED TERMS

ACRONYM	DEFINITION
µg/L	micrograms per liter
ADWL	Acceptable Drinking Water Levels
AME	Acton • Mickelson • Environmental, Inc.
AOIs	areas of interest
ASTs	aboveground storage tanks
ATSDR	Agency for Toxic Substances and Disease Registry
ATSM	American Standard for Testing and Materials
bgs	below ground surface
CCV	continuing calibration verification
CDC	Centers for Disease Control and Prevention
cfs	cubic feet per second
cfu/100 ml	colony-forming units per 100 milliliters
CO_2	carbon dioxide
DIC	dissolved inorganic carbon
DOC	dissolved organic carbon
DRO	diesel range organics
EPA DWAs	US EPA Drinking Water Advisories
EPA MCLs	US EPA Maximum Contaminant Levels
EPA SDWRs	US EPA Secondary Drinking Water Regulations
ft/day	Feet per day
ft^2/day	feet squared per day
GAC	granular activated carbon
GC/MS	Gas chromatography/mass spectrometry
GIS	Geographic Information System
gpm	gallons per minute
GPS	global positioning system
GRO	gasoline range organics
HASP	Health and Safety Plan
ICV	initial calibration verification
IX	ionic exchange
KB	Kelly bushing
lat/long	latitude/longitude
LCS	laboratory control samples
LSND	low solids, non-dispersed
MBAS	methylene blue active substances
MBDCI	Maurice B. Dusseault Consulting Inc.
MCL	Maximum Contaminant Levels
MDL	method detection limit
mg/L	milligrams per liter

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MPN/100 ml	maximum probable number per 100 milliliters
MS/MSD	matrix spike/matrix spike duplicate
mS/cm	millisiemens per centimeter
NAVD88	North American Vertical Datum of 1988
NIH	National Institutes of Health
NTU	nephelometric turbidity units
OBM	oil-based mud
OCSRRS	Oil Contaminated Soil Remediation Ranking System
pCi/L	picocuries per liter
PDS	post digestion spike
psi	pounds per square inch
PVC	polyvinyl chloride
QA/QC	quality assurance and quality control
QAPP	Quality Assurance Project Plan
qPCR	quantitative polymerase chain reaction
RL	reporting limit
RO	reverse osmosis
RPDs	relative percent differences
SAP	Sampling and Analysis Plan
SGCU	silica gel cleanup
SOP	Standard Operating Procedure
SVOCs	semi-volatile organic compounds
TBA	tert-butyl alcohol
TDS	total dissolved solids
TEAP	terminal electron acceptor process
TICs	tentatively identified compounds
TOC	total organic carbon
US EPA	United States Environmental Protection Agency
uS/cm	microsiemens per centimeter
USBR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USDW	Underground Source of Drinking Water
USGS	United States Geological Survey
VOCs	volatile organic compounds
VRP	Voluntary Remediation Program
WDEQ	Wyoming Department of Environmental Quality
WDFG	Wyoming Department of Fish and Game
WOGCC	Wyoming Oil and Gas Conservation Commission
WSEO	Wyoming State Engineer's Office
WSGS	Wyoming State Geological Survey
WY DWEL	Wyoming Drinking Water Equivalent Level
WYPDES	Wyoming Pollutant Discharge Elimination System
YSI	Yellow Springs Instruments

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EXECUTIVE SUMMARY

This Pavillion, Wyoming Area Domestic Water Wells Final Report and Palatability Study (the 2014 Groundwater Investigation) was prepared by Acton • Mickelson • Environmental, Inc. (AME) and the Wyoming Department of Environmental Quality (WDEQ), to provide the results of the investigation into water quality issues within the Pavillion Gas Field (Study Area) in the rural area east of Pavillion, Wyoming that relies on well water.

In response to complaints of taste and odor issues in well water from residents in the Pavillion Gas Field, the United States Environmental Protection Agency (US EPA) conducted field investigation activities from 2009 to 2011 in the area near Pavillion and published a draft report on the results of their groundwater investigation in December 2011. EPA's draft report concluded that hydraulic fracturing fluids may have impacted groundwater in the Study Area. Some reviews however, questioned the major findings in the draft report. In June 2013, the US EPA announced that the agency had no plans to finalize the draft report. Subsequently, the US EPA in coordination with Encana Oil and Gas (USA), Inc. (Encana) and the State of Wyoming agreed that the State of Wyoming would perform a separate investigation of the residents' concerns.

Based on the Framework Document (Appendix A), the State of Wyoming announced in June 2013 that it would further investigate drinking water quality issues in the Study Area. The investigation outlined in the Framework Document included a review of the current body of information available for the water-supply wells in the Study Area and the collection of additional water quality and operational data from water-supply wells in order to assess water quality and identify parameters or conditions that might cause palatability or other concerns. As part of this effort, the WDEQ contracted AME to assist in this investigation as follows:

Conduct the 2014 Groundwater Investigation to evaluate 14 water-supply wells (domestic, irrigation and stock) specified in the Framework Document for water quality, palatability issues, and other concerns. This included the review of historical data and conducting two rounds of sampling.

Evaluate relevant data, conclusions, and recommendations contained in various related documents, including the Wyoming Oil and Gas Conservation Commission (WOGCC) Pavillion Field Well Integrity Review dated October 8, 2014 and Pavillion Field Pit Review dated June 4, 2015 (Pit Review Report).

Assist the WDEQ in preparation of a final report that includes: the findings of the investigation; a discussion of potential sources of any identified water quality impacts; a review of potential treatment options for identified water-quality issues, and considerations for additional work.

AME conducted the following field investigations in 2014: the first round of sampling in the second and third weeks of June 2014, the second round of sampling in the second and third weeks of August 2014, downhole video surveys of the water-supply wells between October 6 and 10, 2014, and interviews with owners of the water-supply wells between October 6 and 9

and on November 3, 2014 (collectively referred to as the 2014 Groundwater Investigation). AME reviewed and evaluated a number of related documents and historical data in 2015. Major findings and conclusions from these efforts are described below.

The reported depths of water-supply wells within an area encompassing 23 sections of land and most of the Pavillion Gas Field and the Study Area, range from 10 to 1,055 ft, with a majority not deeper than 200 ft (60 out of 88) and 7 greater than 700 ft deep. For the 14 water-supply wells that were evaluated as part of the study, reported total depths range from 30 to 675 ft, with 7 of the wells deeper than 200 ft. Depth to groundwater in the study water-supply wells ranged from 5.2 to 270.3 ft bgs (the latter was likely affected (lowered) by pumping).

The Pavillion Gas Field is a conventional reservoir in which gas is produced from permeable sandstones in the Wind River Formation and the underlying Fort Union Formation using vertical wells. Gas in the Wind River Formation appears to have originated mainly from upward migration from deeper gas-bearing zones, most likely due to the absence of a regional confining layer. The shallow Wind River Formation gas and deeper Fort Union Formation gas are similar chemically and isotopically. Evidence suggests that upward gas seepage (or gas charging of shallow sandstones) was happening naturally in the Pavillion area before gas well development.

In the Pavillion Gas Field, non-commercial quantities of gas are known to be present in zones as shallow as 500 feet (ft) below ground surface (bgs) and are possibly present at shallower depths. The spatial density of gas wells is 40-acre spacing per well, and the uppermost perforations in the gas wells are as shallow as 686 ft bgs. Hydraulic fracturing intervals in the Pavillion Gas Field typically start below 1,500 ft bgs, but have been performed as shallow as 1,060 ft bgs. The shallowest depth that was hydraulically fractured within 1,420 ft of the 14 water-supply wells included in the study is 1,397 ft bgs.

Based on a review of gas development and production practices in the Pavillion Gas Field, it is unlikely that hydraulic fracturing fluids (injected into the deeper production zone(s)) have risen to the depths utilized by water-supply wells. The likelihood is negligible that hydraulic fracture well stimulation treatments used in the Pavillion Gas Field have led to fluids interacting with shallow groundwater supplying the study wells (i.e. water-supply well depths, 30 to 675 ft bgs), based on the volume of the treatments (often less than 200 barrels) and the depth (shallowest hydraulic fracturing is generally deeper than 1,500 ft bgs).

There is potential communication of groundwater and/or gas between shallow water-bearing zones and intermediate zones (i.e. below the shallow water-bearing zones and above the gas production intervals) that are both intercepted by gas wells. This is more likely in gas wells where the top of production casing cement is below the surface casing shoe, thereby leaving an open annular space between the production casing and the borehole wall. It should be noted that existing WOGCC rules were followed for all gas wells at the time of their construction. The most likely conditions for vertical flow to occur include: 1) a gas well with an annular space without cement adjacent to production casing, 2) a relatively shallow surface casing in the same gas well, 3) an intermediate pressurized zone, and 4) a permeable groundwater zone that intersects the gas well below the surface casing shoe. Sustained Bradenhead pressure in a gas

well would indicate a greater likelihood of movement of groundwater and/or gas. Water quality in the intermediate zones is expected to be different than in the shallow water-bearing zones, such as higher dissolved solids concentrations, therefore communication between the two zones could introduce water of poorer quality into the shallow water-bearing zones

Based on the results of Bradenhead testing, some gas wells, especially the 11 wells with sustained Bradenhead pressure, have experienced slow gas seepage (and sometimes water seepage).

Analyses of produced gas from tubing and Bradenhead gas samples indicate that the Bradenhead gas is thermogenic, consistent in composition between wells, and similar to the tubing gas from production zones. Bradenhead gas observed in gas wells, however, is likely sourced from intermediate zones containing non-commercial quantities of gas.

Gas in samples obtained from water-supply wells is thermogenic gas that shows signs of alteration by biodegradation and migration. Chemical composition and isotopic signatures of the gas do not suggest a shallow biogenic source.

The potential contribution of gas seepage along gas wells versus natural upward migration of gas is undefined and would be difficult to quantify. Sustained Bradenhead pressure is not direct evidence that gas (and sometimes water) seeping along the wellbore has entered or is entering shallow water-bearing zones in which the water-supply wells are completed. Existing data from the Pavillion Gas Field is insufficient to demonstrate whether this has occurred or is occurring, and the analysis is hindered by the presence of naturally occurring gas in shallow permeable zones.

The general chemical characteristics (major cations and anions) of the groundwater from the water-supply wells included in the 2014 Groundwater Investigation are consistent with those reported for the Wind River Formation across the Wind River Basin. The predominant cation and anion are sodium and sulfate, respectively. Concentrations of sodium (ranging from 79 to 1,400 milligrams per liter [mg/L]), sulfate (250 to 3,500 mg/L), and total dissolved solids (TDS) (560 to 6,350 mg/L) exceed drinking water standards or comparison values in almost all the samples.

A lack of baseline water-quality data that predates development of the Pavillion Gas Field hinders reaching firm conclusions on causes and effects of reported water-quality changes potentially due to gas exploration and production operations.

Exceedances of drinking water standards or comparison values are generally limited to naturally occurring dissolved salts, metals, and radionuclides. Only two organic compounds, one synthetic organic compound (the pesticide beta-BHC) and a phthalate ester (a common laboratory contaminant and a constituent of plastics used in water-supply systems), were detected at concentrations exceeding the applicable drinking water standard or comparison value.

All other organic compounds reported in groundwater samples are at concentrations less than drinking water standards or comparison values and may originate from multiple possible sources.

For example, petroleum constituents (isopropyl benzene and naphthalene) may be attributable to surface spills from fueling vehicles and/or releases from gas well pits. Some organic chemicals reported in the groundwater samples are likely laboratory artifacts (e.g. acetone, methylene chloride, 2-propanol). Reported concentrations of gasoline range organics and diesel range organics may represent a variety of organic compounds, including naturally occurring organic compounds and/or byproducts of bacterial growth.

Geochemical changes associated with the biodegradation of dissolved organic compounds by bacteria including iron-related and sulfate-reducing bacteria have potentially produced constituents that cause poor water palatability, and may be linked to declining well yields. Biodegradation of dissolved organic constituent through sulfate reduction produces sulfides. Also, biodegradation creates chemically reduced groundwater conditions, which increases the solubility of naturally occurring constituents, including metals, such as arsenic, iron, and manganese. Many of the water-supply wells included in the 2014 Groundwater Investigation show the effects of iron-related and sulfate-reducing bacteria, including chemically reduced groundwater and other geochemical changes.

Existing data from former pit location investigations requires more detailed review to assess the potential to impact groundwater quality in water-supply wells. The analysis included in the Pit Review Report could have been more detailed in the assessment of whether the site investigations and/or remediations were sufficient to protect groundwater quality in water-supply wells located within 1,420 ft of the pit locations. Additional analysis could be performed using existing data (e.g. groundwater results from WDEQ Voluntary Remediation Program (VRP) investigations) and augmented with published guidance or studies from other areas to further address this question.

Based on the data collected during this study, and review of reports and data that have been previously published, additional activities for consideration include:

Additional characterization of groundwater constituents that cause palatability issues to assist in designing a method to improve water quality,

Assessment of the relative contribution of potential gas seepage along gas wells versus naturally occurring upward seepage of gas,

Determination of whether conditions are present to allow the potential movement of groundwater and/or gas from intermediate pressurized zones into shallower water-bearing zones,

Continued evaluation of surface pits for potential contribution to water-quality issues in water-supply wells through the VRP process and,

Consideration of other potential sources of petroleum hydrocarbons such as drill cuttings disposal sites and gas production and gathering facilities.

1. INTRODUCTION AND SCOPE OF WORK

In response to complaints of taste and odor issues in well water from residents in the Pavillion Gas Field area east of Pavillion, Wyoming the US EPA conducted field investigations from 2009 to 2011 and published a draft report on groundwater contamination near Pavillion in December 2011. The US EPA concluded that constituents associated with hydraulic fracturing in the Pavillion Gas Field may have impacted the area's groundwater. Some reviews of the draft report questioned the findings in the draft report.

In June 2013, the US EPA announced that the agency had no plans to finalize the draft report or seek peer review, and terminated its request for public comment. Subsequently, the US EPA in coordination with Encana Oil and Gas (USA), Inc. (Encana) and the State of Wyoming agreed that the State of Wyoming would perform a separate investigation of the residents' concerns.

The State of Wyoming announced on June 20, 2013, that the State would further investigate drinking water quality issues in the rural area east of Pavillion, Wyoming (Study Area). The State of Wyoming, with input from the US EPA and Encana, created the Framework Document (Appendix A), which outlined the investigation and Final Report requirements. This scientific investigation would seek to address water quality concerns by evaluating the water quality of water-supply wells selected by the Wyoming Department of Environmental Quality (WDEQ), the integrity of nearby oil and gas wells, and historic use of pits in the PavillionGas Field.

The WDEQ was charged with overseeing the groundwater investigation and the review of historic data and reports. The WDEQ contracted with Acton Mickelson Environmental, Inc. (AME) to assist in this scientific investigation as follows:

- Conduct the 2014 Groundwater Investigation to evaluate 14 water-supply wells (domestic, irrigation, and stock) specified in the Framework Document for water quality, palatability issues, and other concerns. This includes the review of historical reports and data, and conducting two rounds of sampling.
- Evaluate relevant data, conclusions, and recommendations contained in various related documents, including Wyoming Oil and Gas Conservation Commission (WOGCC) *Pavillion Field Well Integrity Review Report* dated October 8, 2014 and *Pavillion Field Pit Review* dated June 4, 2015.
- Determine if further investigation, including additional sampling, is necessary.
- Prepare a final report of the findings of the investigation.

1.1 Rationale for Conducting Groundwater Investigation

Water quality in water-supply wells near the Pavillion Gas Field east of Pavillion, Wyoming was previously assessed by the US EPA and WDEQ, and was found to exceed standards for one or more constituents (e.g. sulfate, total dissolved solids). As a result, the June 20, 2013 Framework

Document called for a review of the current body of information available for the water-supply wells in the Study Area and collection of additional water quality and operational data from the 14 water-supply wells specified by WDEQ to assess water quality and identify other parameters that might cause palatability or other concerns.

1.2 Summary of Previous Investigations and Response Actions

The following summary is primarily drawn from documents in the WDEQ Pavillion Case Files (WDEQ, 2015), along with other cited references.

In September 2004, following the acquisition of the Pavillion Gas Field, Encana sampled water-supply wells located within the Pavillion Gas Field, including water-supply well PGDW05. The sampling was conducted in order to provide baseline water quality data prior to drilling additional gas wells near the property on which PGDW05 is located. There were three gas wells within 1,420 ft of PGDW05 prior to the September 2004 sampling. In November 2004, Encana began drilling another gas well near this property.

In April 2005, following concerns voiced by the owner of PGDW05 about the odor and taste of the well water, Encana sampled PGDW05 in order to investigate if drilling operations were impacting the water quality. In the meantime, Encana began providing bottled water to the owner of PGDW05. Comparison of the September 2004 and April 2005 sample results did not indicate that Encana operations had impacted PGDW05. Nonetheless, in spring 2005, Encana and the owner of PGDW05 tried various restoration efforts (acid washing, wire brushing, video inspection of casing, and chlorine decontamination) to clean up the well.

In June 2005, the owner of PGDW05 first notified the WDEQ of water-quality concerns, and, following discussions with the WDEQ, Encana conducted additional sampling at PGDW05. On October 24, 2005, the Office of the Governor of the State of Wyoming (Wyoming Governor's Office) sent a letter to the owner of PGDW05 indicating that state agencies could not identify a particular cause for any water quality concerns (Wyoming Governor's Office, 2005). Encana subsequently stopped water delivery to the owner of PGDW05.

In December 2005, the WDEQ was notified that the owner of PGDW05 was drilling a replacement water-supply well, and that it had blown out. Encana subsequently plugged the well.

From April 2005 to July 2007, Encana had PGDW05 reworked and sampled. Although odor and sheen were observed in the well water, reported concentrations of petroleum hydrocarbons and other constituents in the samples were less than analytical reporting limits.

In August 2007, Encana installed a sediment-carbon filter at PGDW05 in an attempt to mitigate the reported odor, taste, and clarity issues. Approximately 200 gallons of water were pumped through the two-stage filter, but the water still had a sheen and odor, and the sediment filter was black and coated with a "greasy" material. Additional sampling of PGDW05 was conducted by Encana in late 2007 for other parameters not previously tested (e.g., iron-related and sulfate-reducing bacteria and dissolved methane). Methane and diesel range organics (DRO) were among the chemicals detected in the samples.

A November 2, 2007 memo prepared by Gary Strong of the WOGCC and distributed to the WDEQ and other state agencies provided a review of cement bond and porosity logs from 29 gas wells drilled in the vicinity of PGDW05. Findings from the review include and concluded the following:

- Shallow gas sands (the shallowest identified at 674 ft bgs) were already charged as early as 1981 when gas well Indian 14-2 was drilled.
- Shallow gas (just below 500 ft bgs) is widespread throughout the Study Area and predated reported water quality impacts at PGDW05 and the blowout of the PGDW05 replacement well.
- The blowout at the PGDW05 replacement water-well might not have occurred if it had not been drilled deeper than the 350 ft bgs as approved by the Wyoming State Engineer's Office (WSEO).

In addition to water quality issues at PGDW05, Encana (or its predecessor, Tom Brown Inc.) had also installed a reverse osmosis system on well PGDW20 in 2005 due to complaints by that well owner, and purchased the property on which wells PGDW41A and PGDW41B are located in 2005 due to complaints by that well owner..

In January 2008, the Powder River Basin Resource Council (PRBRC) submitted a letter to the US EPA describing objectionable taste and odor problems in well water near the Pavillion Gas Field (PRBRC, 2008). In July 2008, Pavillion citizens and environmental organizations submitted a letter to the US EPA Region 8, U.S. Bureau of Land Management, Encana, and Devon Energy requesting a human health impact assessment of natural gas development in Fremont County.

In October 2008, Encana conducted additional water sampling at PGDW05 and analysis found tentatively identified compounds (TICs) that were attributed to decaying organic matter in the well.

From March to May 2009, the US EPA conducted Phase I of its field investigation. Water samples were collected from 37 water-supply wells and two municipal water wells in the Pavillion area. Methane and petroleum hydrocarbons were detected in several of the samples. The US EPA concluded that most water-supply wells did not have apparent health concerns, but that there was potentially a connection between the analytical results and oil and gas production activities, though it could not pinpoint any specific source at that time.

In January 2010, the US EPA conducted Phase II of its field investigation by narrowing the scope to an area near 11 water-supply wells in which methane, petroleum hydrocarbons, nitrate, arsenic, and other constituents had been reported in groundwater samples. Twenty-three wells were sampled, including 10 wells that had been previously sampled, and three shallow monitoring wells near three surface pits associated with gas well drilling.

In August 2010, the Agency for Toxic Substances and Disease Registry (ATSDR) reviewed groundwater quality data from the first two phases of the US EPA's investigation. The ATSDR

concluded that 20 of 41 private wells contained compounds associated with petroleum products, including TICs and DRO, all of which were at concentrations less than the state clean-up level, as well as methane at concentrations below the lower explosive limit. Between five and 11 wells, as reported by the ATSDR, contained man-made organic compounds that were either present at concentrations less than health-based screening levels or for which there were no screening levels available (i.e. insufficient toxicity data). The ATSDR stated that the presence of sulfate, iron, and sulfur bacteria may be associated with the odor and taste issues of the water. The ATSDR, unable to identify the root cause of the problem, recommended additional monitoring, expanded chemical analyses, and that affected residents use alternative or treated water supplies until further studies could be completed. Encana began supplying bottled water to affected residents.

In June 2010, the US EPA installed two deep monitoring wells (MW01 to 785 ft bgs and MW02 to 990 ft bgs) intending to differentiate deep versus shallow groundwater quality. Both wells were drilled below the depth of almost all water-supply wells in the area, and above the highest perforated interval for natural gas production.

In September and October 2010, the US EPA conducted its third phase of field investigation by collecting gas samples from the casings of monitoring wells MW01 and MW02, and groundwater samples from both monitoring wells. In addition, groundwater samples were collected from a previously unsampled water-supply well and two previously sampled water-supply wells.

In April 2011, the US EPA conducted Phase IV of its groundwater investigation by resampling monitoring wells MW01 and MW02 with an expanded analyte list that included glycols, alcohols, and low molecular weight acids. Eleven previously sampled water-supply wells were also sampled at this time. High pH, chloride, potassium, petroleum hydrocarbons, and other organic compounds were reported in the samples from the two deep monitoring wells.

In December 2011, the US EPA published its draft report on groundwater contamination near Pavillion. In that draft report, the US EPA suggested that constituents associated with hydraulic fracturing in the Pavillion Gas Field may have impacted the area's groundwater, however, this report was never finalized. An evaluation of the groundwater data collected from the two monitoring wells is discussed in Section 5.9.1.

In April and May 2012, the United States Geological Survey (USGS), at the request of the WDEQ, collected data from the two US EPA deep monitoring wells (MW01 and MW02) to provide an independent assessment of groundwater quality from the wells. The US EPA was also involved in this data collection event. The USGS data indicated that: 1) at monitoring well MW01, the pH did not reach stability after extensive purging and continued to decrease; and 2) monitoring well MW02 could not be sampled due to insufficient yield even after redevelopment. These issues raised doubts on the representativeness of the data collected from monitoring wells MW01 and MW02.

In response to discussions with Pavillion area residents, the 2012 Legislature, with the support of Governor Matt Mead, amended the Wyoming Water Development Commission's construction funding requests to include $750,000 for the Pavillion East Water Supply Project (Level III). The authorizing statute defined the project as follows: "*Design and construction of cistern systems, a water-loading station and appurtenances necessary to make the project function in the manner intended.*" The authorizing legislation directs the following: "*The commission, in coordination with the governor's office, select water committee, department of environmental quality and the Wyoming oil and gas conservation commission shall develop project operating criteria to include, but not limited to the following: the project area, eligibility of residences in the project area to participate in the project and utilization of water sources which would not impact existing uses.*"

An inter-agency working group was formed on March 16, 2012, and consisted of representatives from the Wyoming Governor's Office, WDEQ, WOGCC, and Wyoming Water Development Office (WWDO) to help implement this legislation. This working group completed their work in the middle of November 2012. The cistern area was identified (see Section 2.1) and agreements with rural residents in the area located east of the Town of Pavillion (Pavillion) were prepared and, beginning in mid-March 2013, offered to landowners who expressed an interest in a cistern and met project operating criteria. To date, cisterns have been installed at three of the seven residences included in this study. The remaining four residences are currently receiving bottled water for culinary, drinking and other uses. Note that cisterns have been installed at residences not included in this study.

In June 2013 the US EPA announced that the agency had no plans to finalize the draft report or seek peer review, and later terminated its request for public comment. Subsequently, the US EPA, in coordination with Encana and the State of Wyoming agreed that the State of Wyoming would perform a separate investigation of the residents' concerns.

1.3 Objectives

The objectives of this Study were to:

- Assess the quality of water from the water-supply wells
- Clarify and assess water quality concerns
- Assess the potential for impacts to the quality of water in the water-supply wells by oil and gas wells, related pits and other sources as appropriate
- Identify groundwater constituents that might cause palatability or other concerns in water-supply wells
- Assess the need for further action to address palatability or other concerns with existing groundwater quality. This may include the need for additional testing and analysis, and/or investigation.

1.4 Scope of Work

The general scope of work to accomplish the stated objectives is presented below. Section 3 provides details of the groundwater investigation methodology.

- Prepare Sampling and Analysis Plan (SAP), Quality Assurance Project Plan (QAPP), and Health and Safety Plan (HASP) for field activities
- Conduct a site reconnaissance
- Conduct two groundwater sampling events
- Prepare SAP Addendum for downhole video surveys
- Conduct downhole video surveys
- Conduct well owner interviews
- Review the WOGCC Well Integrity and Pit reports
- Review relevant existing documents
- Verify locations of select gas wells
- Prepare a final report

1.4.1 Water-Supply Wells Included in the 2014 Groundwater Investigation

Fourteen water-supply wells were identified in the Framework Document for inclusion in the 2014 Groundwater Investigation. The criteria established by the WDEQ for selecting the water-supply wells in the 2014 Groundwater Investigation are discussed below.

The WDEQ was charged with evaluating the water-supply wells in the Pavillion area for the likelihood of impacts from oil and gas operations. The WDEQ evaluated all of the water-supply wells located in or immediately adjacent to the Pavillion Gas Field that had been previously identified and/or investigated as having water quality issues. The WDEQ used the following criteria to establish areas of interest (AOIs) within which water-supply wells would be considered for further study:

- The water-supply well was located within the defined boundary of the Pavillion Gas Field.

- The water-supply well was located within 1,000 ft of a gas well that was drilled using a diesel-based or invert drilling fluid.

- The water-supply well was located within 1,000 ft of an earthen drilling or production pit.

- The water-supply well was located within 1,000 ft of a gas well where Bradenhead testing showed gas pressure in the well annulus.

- The water-supply well had indication of the presence of methane, diesel range organics (DRO), gasoline range organics (GRO), volatile organic compounds (VOCs), or semi-volatile organic compounds (SVOCs) based on previous groundwater sampling results.

- The water-supply well was installed deeper than the surface casing of gas wells located within 1,000 ft of it.

Data sources reviewed for the above selection criteria included water-supply well information from WSEO, gas well location and construction information from Encana and the WOGCC, Bradenhead testing data from the WOGCC, groundwater quality data from Encana and the US EPA, information on the production pits from the WDEQ Voluntary Remediation Program (VRP), and additional information from Tribal Pavillion files and the Pavillion Pits and Well Integrity Working Groups. The collected data was then used to create Geographic Information System (GIS) coverages that identified six AOIs. After reviewing the six AOIs, 14 water-supply wells out of 46 wells contained in the AOIs were identified for further investigation (**Table 1**).

It should be noted that PGDW21 listed in the Framework Document is a duplicate listing of PGDW20. As a result, there is no further discussion of PGDW21 in this report. One of the identified water-supply wells, PGDW41, consisted of two wells plumbed together. The WDEQ was able to sample each of these water-supply wells separately, thereby keeping the number of water-supply wells included in the study at 14. The owner of PGDW42 declined to participate in WDEQ's continuing investigation; therefore, no 2014 Groundwater Investigation field activities were conducted at this location. Water quality data for PGDW42 from sampling and analysis conducted prior to the 2014 Groundwater Investigation are included in the data evaluation documented in this report.

Based upon the above, the 2014 Groundwater Investigation includes field activities conducted at the following 13 water-supply wells (study wells): LD02, PGDW05, PGDW14, PGDW20, PGDW23, PGDW30, PGDW32, PGDW33, PGDW41A, PGDW41B, PGDW44, PGDW45, and PGDW49. In addition, well 60F, a previously unidentified shallow (60 ft) well was accessed for groundwater level measurements but was not sampled (**Table 2**).

1.4.2 Water-Supply Well Sampling

Two rounds of water-quality sampling were conducted at each of the 13 water-supply wells included in the 2014 Groundwater Investigation. Summary information for each of the water-supply wells is provided in **Table 2**.

The Framework Document called for two rounds of water-quality sampling within a 12-month period (pre- and post-irrigation season). In order to allow for the time necessary to finalize the scope of work and all necessary project execution documents, secure laboratory services for sample analyses, and plan for and execute the field sampling activities, the first sampling event was conducted in June 2014, after the start of the irrigation season. The second sampling event was conducted in August 2014, near the end of the irrigation season, in an attempt to minimize the likelihood that inclement weather would affect sample collection. Water-quality sampling

was conducted in accordance with the standards and protocol cited in the Framework Document, SAP in Appendix B, QAPP in Appendix C, and HASP in Appendix D.

The reason environmental investigations often perform a high and low groundwater elevation sampling is to determine if there are any effects on shallow (less than 50 feet +/-) water quality due to varying groundwater levels. This is because shallow groundwater monitoring wells can sometimes be influenced by surface irrigation and seasonal (e.g., spring stream flooding) groundwater elevation changes. As explained in the report, only three of the 13 wells are considered shallow: well PGDW33 is 30 feet deep, PGDW45 is 48 feet deep, and PGDW49 is approximately 51 feet deep. Fluctuations in deeper groundwater elevations due to surface irrigation were not expected, nor were they measured during this investigation (see Section 4.2.3 for discussion).

1.4.3 Downhole Video Surveys and Well Owner Interviews

1.4.3.1 Downhole Video Surveys

Downhole video surveys were conducted in LD02, PGDW05, PGDW20, PGDW23, PGDW41A, PGDW41B, PGDW44, and PGDW49 between October 6 and 10, 2014, in accordance with the SAP, QAPP, HASP, and SAP Addendum: Well Video Surveys (SAP Addendum; AME, October 1, 2014). The downhole video surveys were conducted by BESST, Inc., contractor to AME.

The objective of the downhole video surveys was to assess the water-supply wells listed with regard to the following criteria:

- Depth
- Screened interval
- Material type and condition of the casing and screen
- Presence of scaling, sediment, or bacteria
- Well integrity
- Color and clarity of the water
- Gas intrusion
- Water inflow zones
- Other similar observations that may relate to potential water-quality issues

A video camera survey report and a DVD for each of the above wells are included in Appendix E.

1.4.3.2 Well Owner Interviews

Interviews were conducted with the owners of PGDW05, PGDW14, PGDW23, PGDW30, PGDW32, PGDW33, PGDW41A, PGDW41B, PGDW44, PGDW45, and PGDW49 between October 6 and 9, and on November 3, 2014. The owner of wells LD02 and PGDW20 declined to be interviewed.

The objectives of the interviews were to ascertain factors that could potentially affect water quality, including but not limited to, the following:

- Well construction and integrity
- Maintenance history
- Other proximate and pertinent features (e.g., local land use, septic systems)

A well owner interview for each of the aforementioned wells is included in **Appendix F**.

1.4.4 Evaluation of Wyoming Oil and Gas Conservation Commission Pavillion Field Well Integrity Review and Pavillion Field Pits Review Reports

The WOGCC's *Pavillion Field Well Integrity Review* (Well Integrity Review Report) and *Pavillion Field Pit Review* (Pit Review Report) were evaluated to assess the potential impacts of gas wells and associated pits to groundwater quality, palatability, and other concerns. Primary evaluation of the Well Integrity Review Report was conducted by Maurice B. Dusseault Consulting Inc. (MBDCI) for AME, while evaluation of the Pit Review Report was conducted by AME. The data, conclusions, and recommendations from the two reports were evaluated and summarized. Comments and suggestions concerning the related investigations and analyses are also provided. Details of the MBDCI evaluation of the Well Integrity Review Report are provided in **Appendix G** with key issues discussed in this main report. Summaries of AME's evaluation of the two reports are included with the review summaries of other documents described in Section 1.4.5.

1.4.5 Review of Other Documents

Twenty-eight documents were identified by the WDEQ, including the Well Integrity Review Report and Pit Review Report, and 13 additional documents (**Appendix H**) were reviewed by AME with respect to the following, if applicable:

- Analytical data (including quality assurance and quality control [QA/QC] results).
- Descriptions of the constituents identified in the reports and potential sources.
- Summaries and/or conclusions in regards to the quality, palatability, and other concerns with water from the water-supply wells.
- Identification of any analytical data validation issues and limitations this may place on the use of the data.

The review summaries are included in **Appendix I**, which is organized into the following six sections by the primary nature of each of the documents:

1. Geology and Gas Resources
2. Groundwater Resources
3. Pavillion Groundwater Investigations

4. Review of Pavillion Groundwater Investigations
5. Studies on Gas Well Integrity and Oil and Gas Field Pits
6. Other Documents

Supporting information from these documents is utilized in the development of this main report.

2. BACKGROUND

2.1 Site Location and Description

The Study Area, which is equivalent to the cistern area for purposes of this report, is located in Fremont County, Wyoming, east of the Pavillion and within the Pavillion Gas Field. The City of Riverton is approximately 16 miles southeast and Ocean Lake is within 1 mile to the south (**Figure 1**). The cistern area includes approximately 23 square miles encompassing the majority of the Pavillion Gas Field and the adjacent area east of Pavillion. The cistern area was delineated in 2012 by various state agencies including the WOGCC and WDEQ, in an effort to provide alternative domestic water supply to residents within this rural area who depend on groundwater as their primary domestic water supply (Wyoming Water Development Office, 2013).

The Study Area is located within the Wind River Basin. The land surface elevation is approximately 5,400 ft above sea level. Flatter ground, which is cultivated, generally slopes to the east-southeast at a grade of approximately 0.5 percent. Low ridges and hills, generally with no more than 100 ft of relief, rise above the irrigated lands. Topographic features tend to be elongated along the same east-southeast trend.

According to the 2010 census, Pavillion had 95 households in 108 housing units for a total population of 231, up from 165 residents in the 2000 census. The Pavillion school system includes approximately 300 out-of-town students and staff (Gores and Associates, 2011).

2.2 Land Use

The Pavillion area is rural, with the predominant land use being agricultural, comprised mainly of irrigated field crops and stock grazing. Facilities for gas production are interspersed with crop and grazing land (**Figure 2**). Land surface ownership in the Study Area is primarily private, with a portion of federal land administered by the U.S. Bureau of Reclamation (USBR) (**Figure 3**).

2.3 Geology

The Pavillion Gas Field is located near the middle of the Wind River Basin of central Wyoming. The Wind River Basin is a sedimentary and structural basin of approximately 8,500 square miles bounded by the Wind River Range on the west; the Granite Mountains on the south; the Owl Creek Mountains, Washakie Range and Bighorn Mountains on the north; and the Casper arch on the east.

The down-warping of the Wind River Basin trough began in the late Cretaceous during Laramide deformation and increased through the Paleocene. Basin subsidence ceased in the early Eocene, although the deposition of clastic sediments continued. During the Pliocene, the entire region was uplifted and the current cycle of erosion began (USGS, 1970).

The Wind River Basin is asymmetric, with the main trough 3 to 15 miles south of the Owl Creek and Bighorn Mountains. The deepest parts of the basin are as low as 24,000 ft below sea level.

Over 18,000 ft of late Cretaceous through early Eocene sediments of the Lance, Fort Union, and Wind River Formations were accumulated during the Laramide deformation (**Figure 4**). Along the west and southwest margins of the basin, Paleozoic and Mesozoic strata dip 10 to 20 degrees toward the center of the basin, whereas along the northern margins the strata are nearly vertical or overturned. Within the basin, structural features (anticlines, faults, and major synclines) trend northwesterly (USGS, 1970).

Local surficial deposits include Holocene unconsolidated sand and gravel deposits in stream and terrace alluvium, and Holocene/Pleistocene mixed alluvium and colluvium (WSGS, 2011).

The Eocene-age Wind River Formation constitutes the surface bedrock over much of the Wind River Basin, including the Pavillion area (**Figure 5**). The Wind River Formation consists of sandstone, conglomerate, siltstone, and claystone deposited in alluvial fans along the basin's margins near the mountains, and in stream channels, flood plains, lakes and swamps farther from the margins. The bulk of the Wind River Formation consists of red and grayish-green siltstones and claystones, and light-brown sandstones. The sandstones are often arkosic. Paleocurrent studies have mapped the course of the Eocene paleo-Wind River flowing to the east-southeast through the Pavillion area. Fluvial-channel sandstones of the Wind River Formation sometimes form linear ridges (USGS, 1978).

The lower Eocene-age Indian Meadows Formation consists of claystone, sandstone, and limestone, and separates the Wind River Formation from the underlying Fort Union Formation. Its reported thickness ranges from 0 to 750 ft (WSGS, 2012). In the Pavillion area, it is not differentiated on logs of deeper oil and gas wells (WSGS, 2011).

Underlying the Indian Meadows Formation is the Paleocene Fort Union Formation, which consists of sandstone, siltstone, and shale (**Figure 4**). The uppermost Shotgun member of the Fort Union Formation consists of interbedded siltstone, claystone, and sandstone deposited in a lacustrine and fluvial environment (USGS, 1978). The middle member of the Fort Union Formation is the Waltman Shale, a lacustrine shale that is present beneath the eastern portion of the basin. To the west, the lacustrine shale pinches out and is replaced by lacustrine deltaic facies, while farther west, the Waltman Shale member is absent.

The Pavillion Gas Field is located within the inferred area of the lacustrine deltaic facies of the Waltman Shale member. Chemical and isotopic studies of produced gas support the concept that the lacustrine shale facies acts as a confining unit for gas. However, where the lacustrine shale is absent, such as in the Pavillion Gas Field, gases produced from the overlying Wind River Formation are similar to those produced from deeper formations, and thus, probably migrated vertically upward from deeper source rocks (USGS, 1996). The lower unnamed member of the Fort Union Formation consists of clastic debris deposited by streams originating in the margins of the Wind River Basin (USGS, 1978).

Beneath the Fort Union Formation are Paleozoic and Mesozoic sediments, with the greater thickness made up of late Cretaceous sedimentary rocks (WSGS, 2011, 2012).

At the Pavillion Gas Field, the Wind River Formation is exposed along linear ridges and low hills (**Figure 5**). Near the center of the gas field, the top of the Fort Union Formation is at an elevation of approximately 2,000 ft; thus, the overlying Wind River Formation is approximately 3,400 ft thick. The Pavillion Gas Field is approximately centered on a broad structural dome (WSGS, 2011 and Seeland, 1989).

The depths to the logged tops of formations as measured from the Kelly bushing (KB) from well Government Tribal 33X-10 were as follows (KB elevation 5,415 ft, ground surface elevation 5,391 ft): Fort Union 3,365 ft; lower Fort Union 4,567 ft; and Lance (Cretaceous) 6,475 ft. Other formations are listed on the well log, with selected formations as follows: Morrison (upper Jurassic) 16,153 ft, and the Phosphoria (Permian) 18,020 ft (WOGCC, 2015b).

2.4 Surface Water

2.4.1 Basin Hydrology

At Pavillion, the average annual precipitation (1981-2010 period of record) was 7.92 inches per year (NOAA, 2015). Between 2004 and 2014, reported precipitation at Pavillion averaged 8.13 inches and ranged from 12.05 inches in 2005 to 3.27 inches in 2012 (Midvale Irrigation District, 2015a). The average annual precipitation (1907-2009 period of record) at nearby Riverton was 8.89 inches per year (MWH Americas Inc. et al., 2010).

The principal streams and rivers in the Wind River Basin flow to the southeast, parallel to the overall structural trend of the basin. Fivemile Creek flows south-southeast across the Pavillion area into the Boysen Reservoir located on the Wind River approximately 20 miles downstream from the confluence of the Wind River and Popo Agie River.

Historically, Fivemile Creek was reportedly a large gully that was dry much of the year. In 1923, flooding, which was estimated to reach a flow of up to 3,500 cubic ft per second (cfs), enlarged the stream channel. Since the 1920s when irrigation began, perennial flow has been maintained in the middle and lower course of the creek. During the irrigation season, approximately May to September, Fivemile Creek mainly consists of irrigation return flows. Irrigation has also resulted in increased groundwater discharge from adjacent irrigated lands to Fivemile Creek (USGS, 1959).

The average annual flow reported for Fivemile Creek from the USGS gauge near Pavillion (Station number 06244500) was 2.3 cfs. Based on a 25-year record at this location, a seven-day low-flow discharge of 0 cfs is predicted with an indicated two-year recurrence interval (USGS, 1995).

In a compilation of surface water samples obtained from the USGS gauge near Pavillion between 1949 and 1990, the water in Fivemile Creek was characterized as slightly saline (TDS 1,000 to less than 3,000 mg/L) to moderately saline (TDS 3,000 to less than 10,000 mg/L). Based on 47 samples, the median TDS concentration was 3,360 mg/L, with 25 and 75 percentile concentrations of 2,930 and 3,850 mg/L, respectively. Median concentrations of major cations were calcium 460 mg/L, magnesium 140 mg/L, sodium 360 mg/L, alkalinity 170 gm/L, chloride

65 mg/L, and sulfate 2,400 mg/L, based on 51 to 70 samples. The median nitrate concentration in 27 samples was 0.02 mg/L, with a maximum of 0.18 mg/L (USGS, 1996b).

Ocean Lake is located approximately one mile south of the Study Area. It was formed in the 1920s by accumulation of irrigation return flows to a natural depression. The Ocean Lake Wildlife Habitat Management Area was established in the 1940s in cooperation between the USBR and the Wyoming Department of Fish and Game (WDFG) (WDFG, 2015).

Pavillion has a Wyoming Pollutant Discharge Elimination System (WYPDES) permit for its wastewater lagoon system. The design capacity is 20,000 gallons per day, and the system discharges to Pavillion-Ocean Lake Drain #6, which leads to Ocean Lake (WDEQ, 2013). No other WYPDES permit has been identified in the Pavillion area (WDEQ, 2013).

Within Fremont County, surface water supplies about 99 percent of the demand for total off-stream use (592 million gallons per day on average in 1990), while groundwater use was approximately 5.9 million gallons per day on average. Irrigation is the largest off-stream use of surface water, while public water supply was the largest use of groundwater (USGS, 1995).

2.4.2 Irrigation and Surface Soils

The Pavillion area is served by the Midvale Irrigation District, which operates the Riverton Unit of the United States Bureau of Reclamation (USBR). The USBR began construction of the unit in 1920 (USGS, 1969).

The Bull Lake Reservoir, which is on a tributary to the Wind River, stores water for the Midvale Irrigation District and is used to augment natural stream flows in the Wind River. During the irrigation season, water from the reservoir is diverted to the Wyoming Canal. The Wyoming Canal flows to Pilot Butte Reservoir, an off-stream storage near the Wind River, and from there onward to the distribution system in the project area (Midvale Irrigation District, 2015b). Basin-wide reported irrigated acreage is predominantly devoted to alfalfa, with lesser amounts of spring grains, corn, beans, grass hay, and sugar beets (MWH Americas Inc. et al., 2010). The average growing season of 140 days extends from May to September (USBR, 1996), though irrigation deliveries typically commence late April to early May (Midvale Irrigation District, various).

Irrigation in the Pavillion area is large scale, and is afforded by a network of canals and laterals. Within the Pavillion area, estimated seepage rates from ditches and canals are generally 10 percent or less, but with exceptions to the northwest and southeast (**Figure 6**). Mean seasonal consumptive irrigation requirement for alfalfa hay has been estimated at approximately 28 inches for the Riverton area (Pochop et al., 1992). This compares with the actual delivery of water in the Midvale Irrigation District, which was reported between 2.24 and 2.51 acre-ft per acre from 2012 to 2014; 2.26 acre-ft per acre in 2010; and between 1.88 and 2.71 acre-ft per acre from 2001 to 2007 (Midvale Irrigation District, various).

Within the Pavillion area, a majority of the irrigated soils consist of Fivemile silty clay loam (**Figure 7**); it is present on 0 to 3 percent slopes, typically with an A horizon consisting of 0 to 5 inches of silty clay loam, and a C horizon of 5 to 60 inches of stratified silty clay loam to clay

loam to very fine sandy loam. It is classified as well drained. In the Fivemile Creek vicinity, coarser-textured Fivemile sandy clay loam is present. Ridges and hillside soils generally consist of the Apron sandy loam or the Persayo-Oceanet association, a shallow sandy clay loam or fine sandy loam. The course of Fivemile Creek itself is mapped as gullied land. Saline wetland is present in areas near Fivemile Creek and other low-lying areas (USDA, 2015).

2.5 Groundwater

2.5.1 Groundwater Occurrence

Where sufficiently thick, Holocene unconsolidated sand and gravel deposits in stream and terrace alluvium may be a source of groundwater to shallow wells. The sand and gravel are interbedded with finer-grained deposits of silt and clay. Alluvium along Fivemile Creek tends to be relatively finer-grained than other areas in the basin. The reported thickness of most alluvial deposits is less than 50 ft. Generally, the alluvium is a source of water near larger rivers and streams where recharge from surface water is available (WSGS, 2012). Within Fremont County, reported well depths in the Holocene sand and gravel deposits range from 8.6 to 150 ft, and most are used for domestic supplies (USGS, 1995). Given the shallow depth of the alluvial aquifer, groundwater typically is unconfined.

The Wind River Formation has been subdivided into three facies: 1) a lower fine-grained sequence of siltstone, shale, and fine-grained sandstone several thousand ft thick; 2) a middle sequence of green and gray coarse-grained sandstone, conglomerate, and siltstone approximately 1,000 ft thick; and 3) an upper fine-grained sequence of gray and green siltstone, shale, and fine-grained sandstone approximately 800 ft thick (USGS, 1969).

The Wind River aquifer is composed of sandstones and conglomerates (the middle sequence described above) of the Wind River Formation, and is the major source of drinking water in the vicinity of Riverton and Shoshoni (MWH Americas Inc. et al., 2010). The sandstone and conglomerate occur as discontinuous bodies within interbedded siltstones and claystones (USGS, 1969).

In the Wind River aquifer, water-supply wells deeper than 400 ft are common, and depths as much as 2,210 ft have been reported (USGS, 1969 and 1995). Groundwater may occur in unconfined and semi-confined to confined conditions, though most wells are completed within confined aquifers. Depth to water in wells generally ranges from near the surface to about 200 ft, but depths to water of more than 500 ft have been measured. The sandstone and conglomerate bodies vary in size and geometry, and have a range of hydraulic interconnection. Individual lenticular sand bodies may be considered as separate aquifers on a local scale. Differences in water levels as much as 140 ft have been measured in adjacent water-supply wells completed at different depths. Fractures may enhance the permeability of sandstones in areas of structural deformation (USGS, 1969).

Water-supply wells completed in the middle coarse-grained sequence tend to be the most productive; individual wells in the Riverton area yield hundreds of gallons per minute (gpm). The City of Riverton uses six wells for municipal supply, with producing intervals ranging from

75 to 1,750 ft deep and permitted yields ranging from 300 to 725 gpm. The depth of the producing interval for the highest-yielding Riverton well is from 875 to 1,750 ft (WSGS, 2012). Based on aquifer tests performed on the Riverton water-supply wells, the transmissivity is estimated at 1,300 ft squared per day (ft^2/day), with a corresponding hydraulic conductivity of approximately 24 ft per day (ft/day) (USGS, 1959). Water-supply wells completed in the upper fine-grained facies tend to have lower yields. The range of transmissivity for the water-bearing sandstones in the Wind River Indian Reservation is estimated to be between approximately 0.1 to 30 ft^2/day (USGS, 1969). The reported aquifer transmissivity for the water-supply wells in Pavillion ranges from 12 to 150 ft^2/day (Gores and Associates, 2011).

The Fort Union aquifer is comprised of the sandstones of the Fort Union Formation. Given its depth in the Pavillion area (greater than 3,000 ft), groundwater will be present under confined conditions. Within the Wind River Basin, few water wells are completed within the Fort Union aquifer, and those that are completed within the aquifer are used for stock (WSGS, 2012).

The estimated net annual aquifer recharge is between 1 and 5 inches in the Pavillion area, except for along ridges and hills where it is between 0.25 and 0.7 inches per year (WSGS, 2012). In the Pavillion area, most recharge occurs along Fivemile Creek, irrigation canals, and beneath irrigated fields (**Figure 6**).

Historically, the depth to water in shallow wells in the Pavillion area has ranged from 1 to 30 ft bgs. The depth to water in shallow wells fluctuates with the irrigation season, as irrigation is considered the principal source of recharge to the shallow aquifers. In shallow wells located near irrigation ditches and canals, observed seasonal fluctuations have ranged between 4 and 12 ft. The general shallow groundwater gradient in the Pavillion area is inferred to be toward the southeast (USGS, 1959).

Observed groundwater levels in deeper wells, which receive recharge indirectly from surface sources were lower than those in shallow wells and did not fluctuate with the irrigation season (USGS, 1959). In the Riverton area, groundwater flow patterns have been affected by municipal use, with area-wide water levels in wells reportedly reduced by approximately 30 ft (WSGS, 2012).

In the Pavillion area, groundwater is discharged through evapotranspiration, into Fivemile Creek, and through water-supply wells. Fivemile Creek is incised below the water table; therefore the average base flow in the winter months represents groundwater discharge (USGS, 1959).

2.5.2 Pavillion Area Groundwater Use and History of Development

2.5.2.1 Overview

The Wind River aquifer is present at or near the land surface in the Pavillion area (**Figure 5**), and the majority of water-supply wells are completed in this unit. The second-most commonly exploited aquifer is the Holocene unconsolidated alluvial deposits (USGS, 1995). Groundwater in the Pavillion area is used for individual domestic supply, stock, irrigation, and municipal supply for Pavillion.

Pavillion is supplied by five wells completed in the Wind River aquifer. The permitted well yield for these wells ranges from 25 to 40 gpm, and the well depth ranges from 495 to 517 ft. One of the wells is completed as an open borehole, and the remaining four are completed with gravel packs and screens between 300 and 510 ft bgs. In 2005, the town's water system produced 7.3 million gallons of water, or 20,000 gallons per day on average, or 14 gpm. Based on tests of varying duration (approximately 40 minutes to 25 hours) conducted on the town's wells, the reported aquifer transmissivity ranges from 12 to 150 ft^2/day (Gores and Associates, 2011).

In the Pavillion area, local well drillers target what is described as coarse white sand. Driller's logs from gas wells describe the sand as white to light gray, coarse-grained, sub-angular to sub-rounded. Wells completed in this sand include two located approximately 2 miles east-southeast of Pavillion, with depths of 735 and 740 ft, and others northeast of Ocean Lake completed at depths between 900 and 1,055 ft (including wells located in the southeastern corner of the Study Area) (WSEO, 2015). Water quality in these wells is reported to be good, with TDS concentrations ranging between approximately 500 and 800 mg/L. The coarse sands appear to represent Eocene fluvial channel deposits (Gores and Associates, 2011).

A search was made of water-supply well permit records from the WSEO for wells within the Study Area with designated uses as domestic and/or stock. Although not all water-supply wells in the Study Area are included in the WSEO records (approximately half of the study wells have permits, **Table 3**), the permitted well data set is assumed to be generally representative. The records include 97 water-supply wells within the cistern area, including wells fully adjudicated, with complete applications, or incomplete applications (**Figure 8**). The earliest date for a water-supply well is 1906. Additional wells were not recorded until the 1930s, at which point, eight were added between 1930 and 1938 (WSEO). **Appendix J** is a listing of these wells.

Of the 88 water-supply wells within the Study Area with depth information, the reported well depths range from 10 to 1,055 ft. The two deepest wells with listed depths of 1,000 ft and 1,055 ft are located in Section 19, in the extreme southeastern corner of the Study Area (**Figure 8**). The majority of the water-supply wells are not deeper than 200 ft (60 out of 88), with only seven more than 700 ft deep (**Figure 9**).

A review of the WSEO well records identified the nearest permitted irrigation well to the Study Area as located approximately 3 miles south of the Town of Pavillion (WSEO, April 27, 2015).

2.5.2.2 Water-Supply Wells Included in the Study

The earliest reported construction date for the water-supply wells included in the study is 1934 for PGDW33 (**Table 3**). Construction dates are known or estimated for nine of the water-supply wells, and generally are 1984 or earlier, with the exception of LD02 (1994), PGDW23 (2001 or 2002), and PGDW41A (late 2010 or early 2011). Reported total depths range from 30 to 675 ft, and seven of the wells are deeper than 200 ft. The deepest well is PGDW32 (675 ft).

Of the 14 wells included in the study, 10 were originally installed for domestic supply or domestic and stock supply, and three were installed for stock supply or stock supply and irrigation. LD02 was never used because of a reported odor problem (**Table 2**).

2.5.3 Groundwater Quality

2.5.3.1 Overview and Suitability for Domestic Uses

In a compilation of 261 well and two spring sample results obtained from existing literature, the groundwater in the Wind River aquifer across the Wind River Basin was characterized as fresh in approximately two-thirds of the samples (TDS concentration less than 1,000 mg/L). The median TDS concentration was 707 mg/L, and ranged from 224 to 5,110 mg/L. As TDS concentrations increased from fresh to slightly saline (TDS 1,000 to less than 3,000 mg/L), the predominant anion changed from bicarbonate to sulfate. The predominant cations were sodium plus potassium, or calcium and sodium plus potassium (WSGS, 2012).

While most groundwater was generally suitable for domestic use, certain constituents exceeded US EPA Maximum Contaminant Levels (MCLs), Drinking Water Advisories (DWAs), or Secondary Drinking Water Regulations (SDWRs). The percentage of samples analyzed that exceeded a certain constituent are listed in the following table (WSGS, 2012):

Standards	Constituents	Percent Exceedance
EPA MCL or DWAs	Radon-222	80%
	Uranium	29%
	Ammonia	5%
	Selenium	4%
	Boron	1%
	Nitrate	1%
	Nitrate plus Nitrite	1%
	Fluoride	<1%
US EPA SDWRs	Total Dissolved Solids	64%
	Sulfate	56%
	pH	32%
	Manganese	20%
	Dissolved Iron	17 %
	Fluoride	9%
	Chloride	2%

The 1959 USGS groundwater study of the Riverton irrigation project area found that wells less than 200 ft deep generally yielded highly mineralized sulfate water, the result of leaching by infiltrating irrigation water. The water was generally hard (abundant in calcium and magnesium), and concentrations of select dissolved constituents sometimes exceeded the drinking water standards (equivalent to current US EPA SDWRs) of 50 mg/L for iron, 250 mg/L for sulfate, and 500 mg/L for TDS. Water from deeper wells generally contained lower TDS, but a higher percentage of sodium. The concentration of sulfate was proportional to TDS when the TDS concentrations exceeded 1,000 mg/L, while carbonate and chlorides were minor components (USGS, 1959). In a 1969 USGS study in the Wind River Indian Reservation, most of the water in

the upper fine-grained sequence of the Wind River aquifer (approximately 899 ft total thickness) had TDS concentrations greater than 1,500 mg/L (USGS, 1969).

Five municipal water-supply wells are operated by Pavillion and are designated as Well Numbers 1, 4, 6, 7 and 8. These wells are completed to depths between 495 and 517 ft. The reported TDS concentrations in water samples from the wells ranged from 495 to 1,282 mg/L. The predominant cation and anion in water samples from the wells were sodium and sulfate, respectively, with reported concentrations ranging between 173 and 393 mg/L sodium and 300 to 857 mg/L sulfate. The reported sulfate concentrations were greater than the EPA SDWR of 250 mg/L. Well Number 5, completed between approximately 450 and 700 ft bgs, was abandoned due to poor water quality, including TDS concentrations greater than 3,000 mg/L, sulfate concentrations greater than 2,000 mg/L, and sodium concentrations of approximately 1,000 mg/L (Gores and Associates, 2011).

An October 1948 sample from a 482-ft-deep well, A3-2-10db2, had a reported concentration of TDS of 612 mg/L, and the predominant water type was sodium sulfate. The reported concentrations of iron (1.6 mg/L), sulfate (320 mg/L), and TDS (612 mg/L) exceeded the 2012 EPA SDWRs of 0.3, 250, and 500 mg/L, respectively. In the USGS 1969 study, this sample result is reported in a different location, A3-2-10acc, which is located in the same 10-acre parcel as PGDW14 (USGS, 1959 and 1969; USGS NWIS Site Number 431504108373601). This location is consistent with the reported site of the original water-supply well to the west of the residence, which was replaced by PGDW14 (**Table 2**).

Samples were collected on multiple occasions between October 1948 and December 1951 from a 40 ft deep well approximately one-quarter mile west of PGDW32 (A3-2-14aa2, T3NR2ES10 NE ¼ of NE ¼). Reported TDS concentrations in the groundwater samples ranged from 252 to 698 mg/L, and reported sulfate concentrations ranged between 64 and 316 mg/L. The variations in TDS and sulfate concentrations correlated with the irrigation season, with concentrations decreasing during and shortly after the irrigation season due to dilution by infiltrating surface water (USGS, 1959). This same well was sampled in August 1990; the reported TDS concentration was 274 mg/L and the reported sulfate concentration was 67 mg/L (USGS, 1995, also USGS NWIS Site Number 431441108360601).

On August 19, 1991, a sample was collected from well 3N-2E-02cdc01 with a reported depth of 47 ft within the same 10-acre parcel as PGDW05 and PGDW45 (T3NR2ES2 SW¼ of SE¼ of SW¼). Reported concentrations in the sample included sodium (210 mg/L), iron (0.080 mg/L), sulfate (860 mg/L), and TDS (1,430 mg/L). This well was also sampled for six pesticides as discussed in Section 2.5.3.4; reported concentrations were less than the respective method detection limits (MDLs) (USGS, 1996, also USGS NWIS Site Number 431532108364501).

Hydrogen sulfide odors have been reported in water produced from water-supply wells. The water from well A3-3-6cc, 270 ft deep, near the north shore of Ocean Lake, had a moderately low mineral content (TDS concentration of 272 mg/L), but was reportedly unsatisfactory for drinking because of the strong hydrogen sulfide odor and the precipitation of sulfur. Although no

gas analyses were conducted, the problem of hydrogen sulfide in water supplies, particularly in deep wells, was observed at other locations (USGS, 1959).

2.5.3.2 Suitability for Irrigation and Stock Supply

Based on historic water samples from 261 wells and two springs, the 75th percentile of TDS concentrations was 1,190 mg/L, indicating most of the groundwater samples were from sources that would be suitable for irrigation (Wyoming Class II Agricultural standard 2,000 mg/L, Wyoming Class III Livestock standard 5,000 mg/L). The 75th percentile of chloride concentrations (34.5 mg/L) was less than the agricultural standard (100 mg/L). However, the median sulfate concentration (310 mg/L) and sodium-adsorption ratio (16.0) exceeded the agricultural standards (200 mg/L and 8, respectively); meaning that at least half the samples were from sources not suited for irrigation. Sulfate concentrations were generally suitable for livestock, with the 75th percentile (615 mg/L) less than the livestock standard of 3,000 mg/L (WSGS, 2012).

2.5.3.3 Natural Gas in Water-Supply Wells

Gas was reported in a water-supply well in the Pavillion area pre-dating the start of oil and gas development in 1960. During the drilling of a water-supply well in March 1951 ("Camp 9" well), a satisfactory water producing zone was encountered at a depth of 500 ft, but the well was plugged back due to the presence of gas in the water. This "Camp 9" well was located in the NW ¼ of NW ¼ of T4N R3E Section 32, which is adjacent to the northeast corner of the Pavillion Gas Field and the Study Area (USBR, 1951). According to well permit records, the final completion depth of the "Camp 9" well was 300 ft bgs (WSEO, May 11, 2015).

In October 2005, WSEO Permit U.W. 170310 was submitted for a 300 ft water-supply well to replace PGDW05. In December 2005, the well was drilled approximately 150 ft from PGDW05 to a depth of approximately 550 ft bgs. Six-inch polyvinyl chloride (PVC) casing was set at 540 ft bgs with a screen and gravel pack at 520 to 540 ft bgs. While developing the well using air lift, gas began flowing to the surface without controls in place. Subsequently, the Pavillion Gas Field operator, Encana, plugged the well on December 22, 2005. To kill the gas flow, 151 barrels of water were pumped into the well and 10.3 barrels of cement were pumped to the bottom. The top of cement as measured by wire line tools was 518 ft bgs. The casing was perforated at 267 ft bgs but cement could not be pumped in, so the casing was perforated again at 150 ft bgs, and 11.4 barrels of cement were pumped into the shallower perforations (WOGCC, 2014 and WDEQ, 2015).

2.5.3.4 Produced Water Samples

Based on 47 samples of water originating from oil and gas well production zones, Wind River Aquifer groundwater within the Wind River Basin was characterized as slightly saline in approximately half of the samples (TDS 1,000 to less than 3,000 mg/L) with the remainder moderately saline (>3,000 to 10,000 mg/L) to briny (>10,000 mg/L). The predominant cation was sodium; anions were variable except for samples with the greatest TDS concentrations, where chloride was the major anion (WSGS, 2012).

2.5.3.5 Monitoring for Pesticides

In 1998 and 1999, the USGS performed baseline monitoring for pesticides in groundwater throughout Wyoming. The sampling effort focused on wells completed within shallow Holocene alluvial and terrace deposits, which were ranked as the most vulnerable to pesticide contamination. Twenty wells were sampled twice for 21 individual pesticides in late summer 1998 and spring 1999. Three of the sampled wells were located in the Pavillion area. At least one pesticide was detected in 13 of the 20 sampled wells statewide, but concentrations were less than applicable drinking water standards. Of the pesticides, Atrazine was the most frequently detected (17 of 40 samples), followed by Prometron (10 of 40 samples). Reported concentrations in samples from the three Pavillion area wells were less than the respective reporting limits (USGS, 2000).

2.5.4 Underground Sources of Drinking Water

The US EPA delegated administration of the federal Underground Injection Control program to the State of Wyoming on July 15, 1983 and accepted Wyoming's regulations describing its groundwater classification system. The classification system includes classes of groundwater that are equivalent to the EPA's definition of an Underground Source of Drinking Water (USDW), and other classes of groundwater that are not equivalent (i.e. non-USDW).

Wyoming's groundwater classification system (*Water Quality Rules and Regulations* – Chapter 8) defines various classes of groundwater according to type of use for which groundwater is being used (e.g. Domestic (Class 1), Irrigation (Class 2), Livestock (Class 3), Industrial (Class 4), Hydrocarbon (or Mineral or Geothermal) producing (Class 5)) or, in the absence of any existing use, the suitability (i.e. quality) of that groundwater for one or more of the potential uses described above. Wyoming's classification system also includes a class of groundwater (Class 6) that recognizes some groundwater is "Unusable or Unsuitable" for any purpose due to the presence of contaminants or high TDS (>5,000 mg/L), or because it is located (including depth below the surface) such that any use is technologically or economically impractical.

Chapter 8 regulations also define an aquifer as "…a zone, stratum or group of strata that can store and transmit water in sufficient quantities for a specific use," providing the state flexibility in classifying separate parts, or portions of a geologic formation differently: "Classification shall be for a water in a specified locally defined area by named and described aquifer or receiver. Any aquifer or receiver in its regional setting may have one or more classifications by defined area or areas."

In the case of the Wind River Formation in the Pavillion area, groundwater is contained within zones that are used to supply water wells for different purposes (i.e. domestic, irrigation, livestock), as well as within zones that produce natural gas. Accordingly, the state's groundwater classification system distinguishes between different classes of groundwater throughout the Wind River Formation due to the presence of separate and distinct water bearing zones, some of which may be considered USDWs, and others not considered a USDW.

Those zones, stratum, or groups of stratum within the formation that are suitable for domestic, irrigation or livestock use (i.e. TDS < 5,000 mg/L) are classified as Class 1, 2 and 3 groundwater, respectively, and are equivalent to the US EPA's definition of a USDW. Conversely, those zones, stratum, or groups of stratum within the formation that are hydrocarbon producing are Class 5 or Class 6 groundwater (i.e. unusable/unsuitable) for one or more of the reasons described above or are equivalent to non-USDWs as defined by the US EPA. As noted above, historic TDS concentrations in 261 well and two spring samples from the Wind River aquifer ranged up to 5,100 mg/L, and thus on that basis met the 5,000 mg/L criterion for Class 1, 2, or 3 groundwater. In 47 produced water samples, taken from permeable zones deeper than the well and spring samples, TDS concentrations ranged from 1,060 to 38,800 mg/L, and the 75th percentile concentration was 4,860 mg/L (WSGS, 2012).

2.6 Oil and Gas Development

Natural gas and minor amounts of oil are produced from multiple sandstone reservoirs in the Pavillion Gas Field within the lower Wind River Formation and the upper Fort Union Formation at depths ranging from 1,500 to 5,000 ft bgs (Bjorklund, 1978). These relatively shallow gas resources originate from deeper source rocks in the underlying Cody Shale through natural upward migration of the gas over geologic time. This upward migration occurs in part due to the lack of a thick regionally-extensive impervious stratum in the Pavillion Gas Field area such as the Waltman Shale (Johnson and Rice, 1993; USGS, 1996). This lack of a regional "seal" makes the Pavillion Gas Field unique – the gas is only trapped by the shale, siltstone, and claystone that surround the permeable lenses of sandstone. Further, the Pavillion Gas Field is situated near the apex of the Wind River-Fort Union structural dome where gas accumulation is more pronounced.

Non-commercial natural gas-containing sands can be as shallow as 500 ft bgs. In March 1951, during the drilling of the "Camp 9" water-supply well, a satisfactory aquifer was encountered, but the well was plugged back due to the presence of natural gas in the groundwater (Section 2.5.3.3) (USBR, 1951). This documentation of shallow gas predates by several years the drilling of the first producing gas well in the area in 1960.

A review of open-hole geophysical logs obtained from the WOGCC site for wells drilled between 1965 and 1973 indicates the presence of gas-filled porosity at approximately 650, 682, and 827 ft bgs. This suggests the presence of natural gas in groundwater at depths used for domestic water supply prior to extensive commercial development in the Pavillion Gas Field (US EPA, 2011).

A review of cement bond and porosity logs in 29 gas wells drilled in the vicinity of PGDW05 found that most of the gas wells studied had encountered gas-charged sands immediately below surface casing, with many near 500 ft deep (WOGCC, 2007). This suggests the widespread presence of shallow gas sands throughout the Pavillion Gas Field as early as 1981 when gas well Tribal 14-2 was drilled.

All gas wells in the Pavillion Gas Field were constructed vertically using two casing strings cemented using the pump and plug method (WOGCC, 2014). The first string of steel casing (i.e.,

the surface casing) was installed to depths between 197 to 898 ft bgs in wells within the Pavillion Gas Field Study Area. Cement was then pumped down the inside of the surface casing and circulated up the annulus between the casing and the drilled hole in order to anchor the casing to the drilled rock, and to seal the space between the casing and the drilled hole to prevent the migration of oil, water, and gas from one formation and/or strata to another.

After the surface casing was installed, drilling continued below the surface casing to the final depth of the well. A second string of steel casing (i.e., the production casing) was installed to this depth. Cement was then pumped down the casing and circulated up the backside of the casing and the drilled hole. This cement was occasionally, but not always, brought all the way to the surface. In the Pavillion Gas Field, the cement was often only brought up to a height of approximately 1,000 to 2,000 ft bgs. In these cases, remedial cement work was often performed to cover the remaining production casing from the existing top of cement to the surface. A limiting factor for the height of the cement column in the Pavillion Gas Field was the ability of formation pressures to counter the hydrostatic pressure of the column of the cement.

After production casing was set, the drilling rig was removed and a smaller completion rig was brought to prepare the well for oil and gas production. In this phase, the steel casing was perforated using explosive charges. Perforating the casing in the sandstone intervals allows oil and gas to enter the wellbore and be brought to the surface. After the wells were perforated, they were stimulated using either hydrochloric acid or hydraulic fracturing. The majority of these sandstone intervals were hydraulically fractured. Hydraulic fracturing intervals in the Pavillion Gas Field typically start below 1,500 ft bgs, but the shallowest depth hydraulically fractured in the Study Area is 1,397 ft bgs (WOGCC, 2014).

2.6.1 Oil and Gas Development History

Development of the natural gas resources in the Pavillion Gas Field began in 1960 and continued through 2007. Gas production expanded considerably by 2000, and currently, daily gas production is about 10 million cubic ft. Of the 169 gas wells installed between 1960 and 2007 in the Pavillion Gas Field, 98 are currently in active production, 40 are shut-in, and 31 have been plugged and abandoned (WOGCC, 2015). A pipeline transporting the produced gas leads from the Pavillion Gas Field to the east-southeast (WSGS, 2012). **Figure 10** provides a chronological illustration of the history of oil and gas development in the Pavillion Gas Field.

In 1953, Gulf Oil Company drilled the Mae H. Rhodes 1 well to a depth of 11,000 ft into the basal Mesaverde Formation, but the well was plugged and abandoned. In 1960, Shell Oil Company (Shell) drilled the Ora Wells 14-12 to a total depth of 6,505 ft in the Fort Union Formation. The Ora Wells 14-12 is commonly considered the discovery well for the Pavillion Gas Field and is currently shut-in.

Shell continued to develop the gas field and in 1963 received approval for a 640-acre well spacing. Shell drilled a total of 36 wells through 1980 and operated the field until June 1986 when it was acquired by Tom Brown, Inc. Between 1963 and 1983,various other companies (Atlantic Refining Corp., Hickerson Oil Company, Samedan Oil Corp., Palmer Oil and Gas, Kerr

McGee, Damson Oil Corp., Tenneco Oil Company, Impel Energy, Gulf Energy Corp., Hallador Petroleum, Elf Aquitaine Oil and Gas, and Exxon Corp.) drilled an additional 18 wells with most of these wells subsequently being plugged and abandoned.

Between 1993 and 2004, Tom Brown, Inc. drilled 77 wells in the Pavillion Gas Field. In October 2000, Tom Brown, Inc. received approval from the WOGCC to increase well density within most of the Pavillion Gas Field to a 40-acre well spacing. In 2004, Tom Brown was acquired by Encana, which subsequently drilled an additional 36 wells between 2004 and 2006. One additional well was drilled in the field by Devon Energy Corp. in 2007.

Of the 169 Pavillion Gas Field wells, 92 are associated with pits for storing drilling fluids ("mud"), drill cuttings, flowback water, and/or in some cases production fluids. Drilling, completion, and waste handling techniques used in the Pavillion Gas Field varied over time, by operator, and by regulations in effect. A significant change in the WOGCC regulations applicable to pits occurred in 1984, adding more considerations for protection of human health and the environment, such as the required off-site removal of diesel oil-based mud (OBM or invert mud) cuttings or treatment prior to burial, and the prohibition of using reserve pits as production pits.

The 36 wells drilled by Shell between 1960 and 1980 were drilled with the invert mud system circulated to unlined reserve pits at the drill site. The drill cuttings were subsequently buried in the reserve pits. Regulations between 1960 and 1980 did not require treatment of the cuttings prior to burial in a reserve pit, which was standard industry practice. Evidence in the WOGCC files, operator knowledge, and site imagery indicate that these reserve pits were typically partially buried and subsequently used as production pits to store produced water. Records indicate that some of these pre-existing production pits continued to be used by Tom Brown, Inc. until approximately the mid-1990s when the replacement of legacy pits with tanks was completed by the operator.

For the 19 wells drilled between 1953 and 1983 by various other companies, the type of mud used and types of pits used varied with each operator, but most of the wells were drilled using invert mud and unlined reserve pits.

The 114 wells drilled between 1993 and 2007 were drilled using low solids, non-dispersed (LSND) water-based mud systems or water-based potassium chloride (KCl) polymer systems circulated to steel tanks (closed system) without the use of earthen reserve pits for drilling. Lined cuttings pits are associated with 37 of these 114 wells.

2.6.2 Location Verification of Oil and Gas Wells and Associated Pits

In the course of this study, AME identified inconsistencies in the latitude/longitude (lat/long) data between the WOGCC Well Integrity Review Report, Encana data file, summary lat/long and survey reports on the WOGCC website, and aerial imagery. The inconsistencies existed for a significant portion of the oil and gas wells, and even for locations with consistent lat/long data between Encana and the WOGCC, errors of 200 to 300 ft could be identified on aerial imagery.

Since the available location data were insufficient for the study needs, AME proposed to conduct a field verification of select oil and gas well locations.

AME proposed to verify locations where the error between the WOGCC and Encana lat/long was 20 percent or more of the calculated distance to the nearest water-supply well, excluding locations more than one-quarter mile from water-supply wells. AME also proposed to verify locations where the WOGCC and Encana lat/long were consistent but are within a calculated distance one-eighth mile plus 100 ft (i.e. 760 ft) of the nearest water-supply well, given that location errors of 200 to 300 ft were still possible. Fifteen wells met the first criterion and eight wells met the second criterion, resulting in a total of 23 locations for field verification (**Appendix K**).

Field verification was conducted on May 27, 2015 by WDEQ staff and an Encana representative. Field verification included measuring the lat/long of the wellhead using a global positioning system (GPS) unit to sub-meter accuracy, verifying well number if visible, photographing of wellhead location with nearby site features visible for location context, and measuring GPS lat/long of several water-supply wells to allow verification of GPS locations against a known data set.

Results of the field verification are provided in **Appendix K**. All locations but one (gas well Pavillion Fee 13X-3) were located in the field with the wellhead lat/long successfully measured. As anticipated, significant errors were identified between the available lat/long data and field GPS measurements. Errors between the WOGCC and field GPS lat/long are greater than 25 ft at 10 locations and greater than 100 ft at seven locations, with the greatest error of approximately 1,093 ft at gas well Tribal Pavillion 32-10. This latter error appears to be due to a transposition of coordinates for different wells. Errors between the Encana and field GPS lat/long are greater than 25 ft at 19 locations and greater than 100 ft at 18 locations, with the greatest error of approximately 2,364 ft at gas well Pavillion Fee 11-11. The locations having errors greater than 25 feet between the WOGCC and field GPS lat/long also have errors greater than 50 feet between the Encana and field GPS lat/long. The field GPS measurements, verified with a known data set, are used in this study. For other locations with inconsistencies in the lat/long data that were not covered in this field verification, it is suggested that future field verification be conducted to correct any potential inaccuracies, if warranted based on project data quality objectives.

The WOGCC Pit Review Report also has inconsistencies in the pit locations. It appears that where soil or groundwater investigations were performed, pit locations were adjusted on the maps and in the GIS shape files, but the lat/long data in the GIS attribute tables and report tables were not updated and are the same as those of the associated oil and gas wells in the WOGCC Well Integrity Review Report. The adjusted locations for these pits appear to be displayed correctly, therefore the corresponding adjusted lat/long data are adopted in this study. The lat/long data for uninvestigated pits are updated for this report to 2015 field verified GPS measurements of the associated oil and gas wells if available.

2.6.3 Oil and Gas Wells Within 1,420 Ft of Water-Supply Wells

Fifty-two of the 169 Pavillion Gas Field oil and gas wells are located within 1,420 ft (one-quarter mile or 1,320 ft plus a 100 ft buffer; surface distance) of the 14 water-supply wells included in the study (**Figure 11**). Of the 52 wells, 39 are active, four are shut-in, and nine have been plugged. Mineral ownership, location, completion, and production information for these wells are summarized in **Table 4**. The following is a summary of gas wells in relation to each of the 14 water-supply wells included in the study. Detailed information for these gas wells can be found in the Well Integrity Review Report by the WOGCC (2014).

A summary is provided for each water-supply well, or, when water-supply wells are within approximately 100 ft of each other, pairs of water-supply wells. Each summary includes a figure with a map of features within 1,420 ft of the water-supply well (including gas wells and pits); a radial cross-section (including surface elevation, well total depth, and gas well surface casing depth, production casing cement top, and highest perforation); and a timeline (including gas well completion, water-supply well installation, and the construction of the residence or other structures on the property). Water-supply well installation dates and related information are provided in **Table 3**. The construction dates of residences or other structures are from the Fremont County Assessor's records (**Appendix L**). The year built listed for a residence in the assessor's records may indicate the year of improvements made after the original construction date. Other structures are outbuildings including barns, detached garages, equipment storage, loafing sheds, and other utility buildings; some of these may be older residential structures.

<u>LD02 and PGDW20</u>

LD02 and PGDW20 are located on the same property and are separated by 48 ft. Within 1,420 ft of LD02 and PGDW20, there are three gas wells (**Figure 12A**): Pavillion Fee 23-12 (617 and 656 ft from well LD02 and PGDW20 respectively), Pavillion Fee 13-12 (715 and 715 ft), and Unit 22-12 (802 and 758 ft). See **Table 4** for a summary of gas well information.

<u>PGDW05 and PGDW45</u>

PGDW05 and PGDW45 are located on the same property and are separated by 100 ft. Within 1,420 ft of PGDW05 and PGDW45, there are five gas wells (**Figure 12B**): Tribal Pavillion 24-02 (578 and 650 ft), Tribal Pavillion 21-11B (827 and 894 ft), Tribal 14-2 (986 and 895 ft), Pavillion Fee 11-11B (1,118 and 1048 ft), and Pavillion Fee 11-11 (1,389 and 1,383 ft). See **Table 4** for a summary of gas well information.

<u>PGDW14</u>

Within 1,420 ft of PGDW14 there are 11 gas wells (**Figure 12C**): Tribal Pavillion 32-10C (249 ft), Govt Tribal 33X-10 (740 ft), Tribal Pavillion 32-10B (826 ft), Tribal Pavillion 32-10 (958 ft), Tribal Pavillion 33-10W (1,042 ft), Tribal Pavillion 33-10 (1,092 ft), Tribal Pavillion 23-10B (1,098 ft), Tribal Pavillion 33-10B (1,101 ft), Pavillion Fee 31-10B (1,263 ft), USA Tribal 22-10 (1,302 ft), and Tribal Pavillion 23-10 (1,307 ft). See **Table 4** for a summary of gas well information.

PGDW23

Within 1,420 ft of PGDW23 there are eight gas wells (**Figure 12D**): Tribal Pavillion 43-10 (409 ft), Tribal Pavillion 33-10B (549 ft), Tribal Pavillion 43-10B (584 ft), Unit 44-10 (833 ft), Govt Tribal 33X-10 (909 ft), Tribal Pavillion 33-10 (1,030 ft), Tribal Pavillion 34-10 (1,040 ft), and Tribal Pavillion 33-10W (1,124 ft). See **Table 4** for a summary of gas well information.

PGDW30

Within 1,420 ft of PGDW30 there are 10 gas wells (**Figure 12E**): Pavillion Fee 41-10B (670 ft), Pavillion Fee 41-10 (755 ft), Tribal Pavillion 44-03 (792 ft), Pavillion Fee 31-10 (811 ft), Unit 41X-10 (898 ft), W.E. Lloyd 1 (1,185 ft), Pavillion Fee 34-03 (1,234 ft), Pavillion Fee 34-03R (1,234 ft), Tribal 42-10 (1,281 ft), and Tribal Pavillion 44-03C (1,393 ft). See **Table 4** for a summary of gas well information.

PGDW32

Within 1,420 ft of PGDW32 there are two gas wells (**Figure 12F**): Tribal Pavillion 12-13 (576 ft) and Pavillion Fee 21-13 (1,100 ft). See **Table 4** for a summary of gas well information.

PGDW33

Within 1,420 ft of PGDW33 there is one gas well (**Figure 12G**): Tribal Pavillion 12-13 (462 ft). See **Table 4** for a summary of gas well information.

PGDW41A and PGDW41B

PGDW41A and PGDW41B are located on the same property and are separated by 6 ft. Within 1,420 ft of PGDW41A and PGDW41B, there are eight gas wells (**Figure 12H**): Pavillion Fee 13-03W (480 and 474 ft), Pavillion Fee 43-04 (652 and 654 ft), Pavillion Fee 14-03W (761 and 761 ft), Mae H. Rhodes 1 (1,028 and 1,029 ft), Pavillion Fee 13X-3 (1,076 and 1,071 ft), Pavillion Fee 44-04 (1,125 and 1,131 ft), Pavillion Fee 14-03B (1,372 and 1,373 ft), and Blankenship 4-8 (1,385 and 1,383 ft). See **Table 4** for a summary of gas well information.

PGDW42

Within 1,420 ft of PGDW42 there are four gas wells (**Figure 12I**): Pavillion Fee 31-9 (770 ft), Tribal 21-9 (781 ft), Pavillion Fee 32-09W (920 ft), and Maxson 32-9 (1,230 ft). See **Table 4** for a summary of gas well information. See **Table 4** for a summary of gas well information.

PGDW44

Within 1,420 ft of PGDW44 there are 10 gas wells (**Figure 12J**): Govt Tribal 33X-10 (311 ft), Tribal Pavillion 33-10W (582 ft), Tribal Pavillion 33-10 (607 ft), Tribal Pavillion 33-10B (639 ft), Tribal Pavillion 32-10C (758 ft), Tribal Pavillion 32-10B (1,130 ft), Tribal Pavillion 23-10C

(1,187 ft), Tribal Pavillion 23-10 (1,237 ft), Tribal Pavillion 23-10B (1,275 ft), and Tribal Pavillion 34-10 (1,384 ft). See **Table 4** for a summary of gas well information.

PGDW49

Within 1,420 ft of PGDW49 there are 10 gas wells (**Figure 12K**): Pavillion Fee 12-11B (643 ft), Pavillion Fee 41-10 (799 ft), Tribal 42-10 (814 ft), Pavillion Fee 41-10B (874 ft), Pavillion Fee 11-11B (898 ft), Unit 41X-10 (1,040 ft), Pavillion Fee 11-11 (1,172 ft), Tribal Pavillion 42-10B (1,191 ft), Pavillion Unit 12-11 (1,346 ft), and Pavillion Fee 12-11W (1,412 ft). See **Table 4** for a summary of gas well information.

2.6.4 Pits within 1,420 Ft of Water-Supply Wells

There are 25 pits that are either within 1,420 ft of the 14 water-supply wells or associated with gas wells that are within 1,420 feet of the 14 water-supply wells (**Figure 13**). Of the 25 pits, 12 are reserve pits associated with wells drilled between 1953 and 1980. Of the 12 reserve pits, 11 were used to contain invert mud, and 10 of those pits were subsequently used as production pits. The remaining 13 pits are lined cuttings pits associated with wells drilled between 1993 and 2005. Of the 13 lined cuttings pits, four were associated with the use of a KCl polymer system and the remaining nine were associated with the use of a LSND mud system. Location, type, and investigation status for these pits are summarized in **Table 5**. The following is a summary of these pits in relation to each of the 14 water-supply wells included in the study. Detailed information for these pits can be found in the pit review by the WOGCC (2015). A pit summary is provided below for each water-supply well, or each pair of water-supply wells when water-supply wells are within approximately 100 ft of each other. The pit investigation status and/or recommendation for further investigation correspond to those provided by the WOGCC (WOGCC, 2015). Since the publication of the WOGCC Pits Review Report, four of the eight pits enrolled in the Wyoming VRP have been granted Certificates of Completion (COC). The VRP website has more information on remediation and closure of these sites (http://deq.wyoming.gov/media/uploads/150917_vrp_site_list.pdf). The pit associated with Blankenship 4-8 was granted a COC on April 30, 2015, Tribal 14-2 pit was granted a COC on April 29, 2015, the Tribal Pavillion 21-11 pit was granted one on June 16, 2015, and the Tribal Pavillion 14-12 pit was granted one on April 29, 2015.

LD02 and PGDW20

LD02 and PGDW20 are located on the same property and are separated by 48 ft. Within 1,420 ft of LD02 and PGDW20, there is only one pit: Unit 22-12 (882 and 837 ft, respectively). Pit Unit 22-12 is an invert mud-type reserve/production pit, has undergone soil remediation, and is being monitored for groundwater contamination. The surface layout and pit type are illustrated on **Figure 12A**, and a summary of pit information can be found on **Table 5.**

PGDW05 and PGDW45

PGDW05 and PGDW45 are located on the same property and are separated by 100 ft. Within 1,420 ft of PGDW05 and PGDW45, there is only one pit: Tribal 14-2 (1,174 and 1,079 ft,

respectively). Pit Tribal 14-2 is an invert mud-type reserve/production pit and has undergone soil and groundwater remediation. The pit was issued a COC in April 2015. The surface layout and pit type are illustrated on **Figure 12B,** and a summary of pit information can be found on **Table 5.**

PGDW14

Within 1,420 ft of PGDW14 there are seven pits: Govt Tribal 33X-10 (650 ft), Tribal Pavillion 32-10 (958 ft), Tribal Pavillion 33-10 (1,092 ft), Tribal Pavillion 23-10B (1,098 ft), Tribal Pavillion 33-10B (1,101 ft), Tribal Pavillion 23-10 (1,307 ft), and USA Tribal 22-10 (1,474 ft; the gas well is within 1,420 feet of PGDW14).

Pit Govt Tribal 33X-10 is an invert mud-type reserve/production pit, has undergone soil remediation, and is recommended for further investigation. USA Tribal 22-10 is an invert mud type reserve/production pit, was determined to require no soil remediation, and is recommended for further investigation. Pits Tribal Pavillion 32-10, Tribal Pavillion 23-10B, Tribal Pavillion 33-10B, and Tribal Pavillion 23-10 are LSND mud-type cuttings pits and are determined to require no investigation. Tribal Pavillion 33-10 is a KCl polymer-type cuttings pit and is determined to require no investigation. The surface layout and pit type are illustrated on **Figure 12C,** and a summary of pit information can be found on **Table 5.**

PGDW23

Within 1,420 ft of PGDW23 there are six pits: Tribal Pavillion 43-10 (409 ft), Tribal Pavillion 33-10B (549 ft), Tribal Pavillion 43-10B (584 ft), Unit 44-10 (723 ft), Tribal Pavillion 33-10 (1,030 ft), and Govt Tribal 33X-10 (1,111 ft).

Pit Tribal Pavillion 43-10 is a KCl polymer-type cuttings pit, was determined to require no investigation, and is recommended for investigation to determine the need for additional work at KCl polymer-type cuttings pits. Pits Tribal Pavillion 33-10B, and Tribal Pavillion 43-10B are LSND mud-type cuttings pits and are determined to require no investigation. Pits Unit 44-10 and Govt Tribal 33X-10 are invert mud-type reserve/production pits, have undergone soil remediation, and are recommended for further investigation. Tribal Pavillion 33-10 is a KCl polymer-type cuttings pit and is determined to require no investigation. The surface layout and pit type are illustrated on **Figure 12D**, and a summary of pit information can be found on **Table 5.**

PGDW30

Within 1,420 ft of PGDW30 there are four pits: Tribal Pavillion 44-03 (792 ft), Unit 41X-10 (1,003 ft), Tribal 42-10 (1,281 ft), and W.E. Lloyd 1 (1,342 ft).

Pit Tribal Pavillion 44-03 is an LSND mud-type cuttings pit and is determined to require no investigation. Pit Unit 41X-10 is an invert mud-type reserve/production pit, was determined to require no soil remediation, and is recommended for further investigation. Pit W.E. Lloyd 1 is an invert mud-type reserve/production pit and is determined to require no soil remediation. Pit

Tribal 42-10 is a KCl polymer-type cuttings pit and is determined to require no investigation. The surface layout and pit type are illustrated on **Figure 12E,** and a summary of pit information can be found on **Table 5.**

PGDW32

Within 1,420 ft of PGDW32, there is one pit: Tribal Pavillion 12-13 (495 ft). Pit Tribal Pavillion 12-13 is an invert mud-type reserve/production pit, was not located during site assessment, and is recommended for further investigation. The surface layout and pit type are illustrated on **Figure 12F,** and a summary of pit information can be found on **Table 5.**

PGDW33

Within 1,420 ft of PGDW33, there is one pit: Tribal Pavillion 12-13 (577 ft). Pit Tribal Pavillion 12-13 is an invert mud-type reserve/production pit, was not located during site assessment, and is recommended for further investigation. The surface layout and pit type are illustrated on **Figure 12G,** and a summary of pit information can be found on **Table 5.**

PGDW41A and PGDW41B

PGDW41A and PGDW41B are located on the same property and are separated by 6 ft. Within 1,420 ft of PGDW41A and PGDW41B, there are three pits: Mae H. Rhodes 1 (1,028 and 1,029 ft, respectively), Pavillion Fee 13X-3 (1,076 and 1,071 ft, respectively), and Blankenship 4-8 (1,486 and 1,484 ft, respectively; the gas well is within 1,420 feet of PGDW41A and PGDW41B).

Pit Mae H. Rhodes 1 is a water-based mud-type reserve pit and is determined to require no investigation. Pit Pavillion Fee 13X-3 is an LSND mud-type cuttings pit and is determined to require no investigation. Pit Blankenship 4-8 is an invert mud-type reserve/production pit, is determined to require no soil remediation, has undergone groundwater remediation and was issued a COC in April 2015. The surface layout and pit type are illustrated on **Figure 12-H,** and a summary of pit information can be found on **Table 5.**

PGDW42

Within 1,420 ft of PGDW42 there are three pits: Pavillion Fee 31-9 (475 ft), Tribal 21-9 (928 ft), and Maxson 32-9 (1,230 ft).

Pit Pavillion Fee 31-9 is an LSND mud-type cuttings pit and is determined to require no soil remediation. Pit Tribal 21-9 is an invert mud-type reserve/production pit and has undergone soil remediation. Pit Maxson 32-9 is an invert mud type reserve pit, was determined to require no investigation, and is conditionally recommended for investigation. The surface layout and pit type are illustrated on **Figure 12I,** and a summary of pit information can be found on **Table 5.**

PGDW44

Within 1,420 ft of PGDW44 there are six pits: Govt Tribal 33X-10 (505 ft), Tribal Pavillion 33-10 (607 ft), Tribal Pavillion 33-10B (639 ft), Tribal Pavillion 23-10C (1,187 ft), Tribal Pavillion 23-10 (1,237 ft), and Tribal Pavillion 23-10B (1,275 ft).

Pit Govt Tribal 33X-10 is an invert mud-type reserve/production pit, has undergone soil remediation, and is recommended for further investigation. Pits Tribal Pavillion 33-10B, Tribal Pavillion 23-10C, Tribal Pavillion 23-10, and Tribal Pavillion 23-10B are LSND mud-type cuttings pits and are determined to require no investigation. Tribal Pavillion 33-10 is a KCl polymer-type cuttings pit and is determined to require no investigation. The surface layout and pit type are illustrated on **Figure 12J,** and a summary of pit information can be found on **Table 5.**

PGDW49

Within 1,420 ft of PGDW49 there are three pits: Tribal 42-10 (814 ft), Unit 41X-10 (1,140 ft), and Pavillion Unit 12-11 (1,346 ft).

Pits Tribal 42-10 and Pavillion Unit 12-11 are KCl polymer-type cuttings pits and are determined to require no investigation. Pit Unit 41X-10 is an invert mud-type reserve/production pit, was determined to require no soil remediation, and is recommended for further investigation. The surface layout and pit type are illustrated on **Figure 12K,** and a summary of pit information can be found on **Table 5.**

3. 2014 GROUNDWATER INVESTIGATION METHODOLOGY

The procedures followed during this investigation for measurements of water levels, groundwater sampling, decontamination, field measurements, sample custody, and quality assurance/quality control are described in the SAP and the QAPP. The work was conducted in accordance with the HASP.

3.1 Water-Supply Well Sampling

The Framework Document (**Appendix A**) identifies 14 water-supply wells to be included in the study, which includes sampling of each well. PGDW21 is a duplicate listing of PGDW20 (DEQ, 2015, personal communication) and therefore reduces the actual number of wells in the Framework Document to 13 wells. However, well PGDW41 listed in the framework document is actually two adjacent water-supply wells, which are designated PGDW41A and PGDW41B in this study. The two wells are connected to a single supply manifold. Some previous studies did not differentiate the wells, and a combined flow was sampled. The wells were sampled individually by selectively turning the power off and on to each well pump. This raised the number of study wells back up to 14 (**Table 2**).

Access to well PGDW42 was not granted by the well owner for the 2014 sampling events, so only historic data is used for this well. Therefore, a total of 13 wells were sampled in 2014. In addition, well 60F was accessed for groundwater level measurements but was not sampled. In summary, this study includes 14 water-supply wells, 13 of which were sampled (study wells) (**Table 2**).

Private water-supply wells were sampled twice: once near the beginning of the irrigation season and once near the end of the irrigation season. The first sampling event occurred during the second and third weeks of June 2014, and the second sampling event occurred during the second and third weeks of August 2014. Written access agreements to 13 water-supply wells were obtained by the WDEQ in advance of the field work.

3.1.1 Selection of Sampling Locations

On May 21 and 22, 2014, AME personnel completed a reconnaissance of water-supply wells in the sampling program. Information obtained during the site reconnaissance for each proposed sampling location included the sampling point, wellhead configuration, and location for purge water discharge (**Table 2**).

In general, selected sample locations met the following characteristics:

- Upstream of the pressure tank, when present, unless otherwise noted.
- Upstream of treatment systems or other equipment.

- An accessible spigot or frost-proof hydrant to which a fitting for sampling equipment could be attached.

The sampling points for PGDW05, PGDW20, PGDW30, PGDW33, PGDW41A, and PGDW41B were located downstream of pressure tanks. Establishing sampling points upstream of the pressure tanks would have required modifications to the owners' plumbing systems. PGDW41A and PGDW41B were connected to a manifold ahead of the sampling point and were isolated during sampling using the circuit breakers supplying power to the individual pumps.

3.1.2 Groundwater Level Measurements

Groundwater level measurements were collected prior to sampling at water-supply well locations that were accessible and equipped with an access port at the top of the well casing. In June, groundwater level measurements were collected from 60F, LD02, PGDW32, PGDW44, PGDW45, and PGDW49. In August, groundwater level measurements were collected from 60F, LD02, PGDW32, PGDW44, PGDW45, and PGDW49. Except for LD02, these water-supply wells were equipped with downhole pumps, piping, and cables. Measurements were obtained using an acoustic water level meter in accordance with the Standard Operating Procedure (SOP) for Groundwater Level Measurements, Acoustic Meter provided in the SAP.

3.1.3 Water-Supply Well Sampling

In June and August 2014, groundwater samples were collected from the 13 study wells (**Table 6**). Well purging, monitoring of field parameters, and sample collection were performed in accordance with the SOP for Groundwater Sampling, Private Water-Supply Wells (SAP).

To minimize atmospheric contact and potential ambient contamination, a dedicated sampling manifold made of non-contaminating materials was attached to the sampling point and used to collect groundwater samples. Specifically, the manifold consisted of a polyethylene Y-adapter hose fitting with valves, connected to the sampling point to allow for diverting a portion of the flow in order to monitor groundwater parameters and collect groundwater samples. The sampling portion of the manifold was fitted with ¼-inch fluoropolymer tubing, tees, and inline valves to control flow separately to the sample containers and the flow-through cell used to measure field parameters. The other branch of the two-way hose fitting led to a discharge line fitted with a ¾-inch ball valve and totalizing flow meter.

In general, a minimum of three casing volumes was purged from each well prior to sample collection (**Table 6**). A portion of the purging for PGDW23, PGDW30, PGDW32, and PGDW33 was accomplished by the owners operating the well before the scheduled sampling. The purge rate was estimated when the sampling crew arrived on site in the morning. Wells PGDW20 and PDGD33 were located approximately 250 and 1,200 ft, respectively, from the water hydrants where the samples were collected (**Table 2**). The total volume purged before collecting samples at these two wells included an allowance for the estimated volume of the piping between the well and the sampling point (**Table 6**).

During the June and August sampling events, three casing volumes were not purged prior to sample collection at three of the water-supply wells:

- PGDW05. The owner reported a low yield. The well was purged at an average rate of between 2 and 3 gpm until field parameters stabilized, then sampled.

- PGDW41A. During the June sampling event, the pump began to surge after purging at a rate of approximately 6 gpm for 1 hour. The pump was turned off for approximately one-half hour, and then pumping was resumed at approximately 3 gpm. Samples were collected after field parameters stabilized. During the August sampling event, the well was purged at approximately 3 gpm until field parameters generally stabilized; an increase in dissolved oxygen at the end of purging may have indicated that the water level was nearing the pump intake.

- LD02. The well was not equipped with a downhole pump, so it was not purged before sampling.

Field water-quality parameters were measured during purging which continued until five consecutive measurements of temperature, specific conductance, pH, dissolved oxygen, and turbidity had stabilized within the specified criteria (**Table 7**). Accordingly, in some instances, purging continued beyond three casing volumes to allow for stabilization of field parameters. In addition to the parameters monitored for well purge stability criteria mentioned above, field measurements were recorded for oxidation-reduction potential and salinity.

LD02 was sampled using single-use 36-inch Hydrasleeve™ grab sampling devices that were manually lowered and withdrawn from the well. For sample aliquots requiring filtration, a peristaltic pump and Teflon® tubing were used to transfer the water from the grab sample device to the filter prior to the sample containers. An initial attempt was made in June to sample LD02 using a downhole submersible pump, however, the pump starting torque created a twist in the discharge hose that prevented water flow. During the June sampling event, a single set of field water-quality parameters was collected prior to sampling. During the August sampling event, an insufficient volume of groundwater was collected to obtain field water-quality parameters.

The casing volume of PGDW32 was estimated in advance of the sampling events based on a total reported depth of 900 ft. Due to large estimated casing volume and long purge times, the samples were obtained before an estimated three casing volumes were purged. This was recorded on the field notes. Subsequently, upon review of the WSEO well permit, the actual depth of PGDW32 was found to be 675 ft bgs. Consequently, the actual casing volume was less than the original estimate, and the purging was sufficient to remove three casing volumes before sampling.

Once field water-quality parameter measurements had stabilized, groundwater samples were collected. Samples were analyzed for a suite of 39 separate analyses/methods, which required 46 individual sample containers (**Table 8A**). Based upon USGS guidance (USGS, 2006) samples

were collected in a pre-determined order. Sample analyses, containers, preservatives, and holding times are listed in **Table 8B** in order of sampling.

3.1.4 Field Parameter Measurements

Temperature, specific conductance, pH, dissolved oxygen, turbidity, and oxidation-reduction potential measurements were collected using a Yellow Springs Instruments (YSI) Model 6920 multi-parameter water-quality meter equipped with a flow-through cell during the well purging. Daily instrument calibration was performed (**Table 7**).

Ferrous iron was measured in the field using a Hach Model DR890 portable colorimeter in accordance with Hach method 8146 (**Table 7**). Results were recorded on forms along with other field parameters.

3.1.5 Field Quality Control Sampling

Quality-control samples included field duplicates, field blanks, and matrix spike/matrix spike duplicate (MS/MSD) samples in accordance with the SAP and QAPP (**Table 6)**.

Field duplicates were collected at a rate of one for each sampling event. Duplicate samples were obtained from wells that met the following criteria: the sampling point was ahead of the pressure tank, and pump rate and volume were sufficient to collect field parameters plus the required volume for the sample containers. Field duplicate samples were collected for the full suite of analytical parameters, following collection of the entire primary sample.

Field blanks were collected at a rate of one for each sampling event. These were obtained by pouring organic-free deionized water through the sampling manifold to fill the sample containers.

An MS/MSD sample was collected during each sampling event and consisted of a sample of triplicate volume. Wells selected for MS/MSD samples had sufficient yield to collect field parameters and the required volume for the sample containers. The MS/MSD samples were analyzed for a subset of analytical parameters where MS/MSDs are typically utilized by the analytical laboratory (**Table 8A**). Sample containers were filled in the same order as the primary samples (**Table 8B)**.

Trip blanks were included in each cooler that contained samples for: VOCs by EPA Method 8260B, gasoline range organics (GRO) by EPA Method 8015D, and dissolved gases by RSK-SOP 175 (**Table 8A**). Trip blanks were prepared by the laboratory and consisted of sample containers filled with organic-free deionized water.

3.1.6 Sample Analysis, Preservation, and Handling

Samples were analyzed for dissolved gases, general chemistry (including major cations and anions, alkalinity, nutrients, sulfide, and TDS), microorganisms, radiochemistry, semi-volatile organic compounds, (SVOCs, including pesticides, herbicides, fungicides, and DROs), stable

isotopes (isotopes of methane, ethane, dissolved inorganic carbon, and dissolved nitrate), trace metals (total and dissolved), and VOCs, including volatile organic acids, glycols, and GRO (**Table 8A**). Groundwater samples were collected into certified-clean and pre-preserved containers provided by the laboratory. Only sample containers appropriate for the intended analyses were used.

Since dedicated sampling equipment was used, field blanks were obtained for a subset of parameters judged to be most susceptible to contamination from the sampling equipment or ambient conditions. The subset included microorganisms, VOCs, GRO, volatile organic acids, and SVOCs (**Table 8A**).

Samples for dissolved metals, isotopes of carbon in dissolved inorganic carbon, and isotopes of nitrogen and oxygen in dissolved nitrate were filtered using single-use certified pre-cleaned, 0.45 micron (µm) inline filter cartridges fitted to the sample fill tubing (**Table 8B**).

In accordance with the SAP, in the event that field turbidity readings remained above 20 nephelometric turbidity units (NTU), only filtered (i.e. dissolved) samples for trace metals were collected. This only occurred at PGDW41B where fine sand was reported in the groundwater samples. This may be a result of poor well construction and/or completion. At the remaining wells, turbidity readings were below 20 NTU, and thus samples were collected for both total and dissolved metals concentrations.

After collection, the samples were labeled and placed into a cooler and packed with water ice. The internal temperature of the coolers was maintained at approximately 4 degrees Celsius. A temperature blank accompanied each cooler. Sample containers for analysis of volatile constituents (VOCs by EPA Method 8260B, GRO by EPA Method 8015D, and dissolved gases by RDK-SOP 175) were placed in the same cooler as the trip blank samples.

When preparing coolers for shipment via common carrier, bubble wrap was placed in layers on the bottom and around the sides of the cooler to further insulate and prevent breakage during transport to the laboratory. Glass sample containers were wrapped in plastic bubble wrap and tightly packed in the cooler. The cooler was then topped off with water ice. Any voids in partially-full coolers were filled with spare plastic sample containers to prevent samples from shifting and breaking during transport. Prior to transferring the coolers to the common carrier for shipment to the laboratory, they were topped off with water ice once again, sealed shut with packaging tape, and two custody seals were placed on opposing ends.

Samples for analysis for microorganisms and sulfide by Precision Analysis in Riverton, Wyoming (Precision) were carried in a cooler packed with water ice and hand delivered on the same afternoon that samples were collected.

A chain-of-custody record was filled out for every sample and accompanied each shipment of samples to analytical laboratories. Chain-of-custody records for samples analyzed by Precision were hand delivered along with the samples.

3.1.7 Data Validation and Reporting

The samples were analyzed by Curtis and Tompkins Laboratories in Berkeley, California, Isotech Laboratories, Inc., in Champaign, Illinois, and Precision Laboratory in Riverton, Wyoming (**Table 8A**). Curtis and Tompkins transferred some sample containers to subcontracted laboratories:

- Agriculture & Priority Pollutants Laboratories, Inc., Clovis, California
- GEL Laboratories, Charleston, South Carolina
- Microbac Laboratories, Inc., Marietta, Ohio
- TestAmerica, Inc., Tallahassee, Florida
- Weck Laboratories, Inc., City of Industry, California

The reports from all eight laboratories were reviewed for accuracy, precision, representativeness of actual conditions, and comparability with other data during the validation process. Data validation review was performed by Veridian Environmental, Inc., (Veridian) of Davis, California, using the analytical data and supporting documentation provided by each laboratory in accordance with the SAP and QAP. The reviewers performed a comprehensive review, including reconstruction of laboratory results (Level IV review) on 31 validation reports and an independent review of all findings (Level III review) on the remaining 97 data validation reports.

The quality control indicators reviewed by Veridian included field duplicates, laboratory method blanks, field blanks, trip blanks, holding times, MS/MSDs, laboratory duplicates, laboratory control samples (LCS), initial calibrations, initial calibration verification (ICV), continuing calibrations, serial dilutions, and/or post digestion spike (PDS) analyses. The quality control checks performed for each analysis were selected based on standard methodology and laboratory specific procedures. Based on the evaluation of quality control indicators, log sheets, and analyst notes provided, Veridian assigned qualifier flags to the data as follows:

- J - The analyte was positively identified, but the reported numerical value is an approximate concentration of the analyte in the sample.
- J/PM or JP - Reported values are estimated and the decision to use the data is based on additional information.
- U - The analyte was analyzed for, but was not detected at or above the reported sample quantitation limit.
- UJ - The analyte was not detected at or above the reported sample quantitation limit and the reported quantitation limit is approximate and may or may not represent the actual limit necessary to accurately and precisely measure the analyte in the sample.

- UJ/PM or UP - The analyte was analyzed for but not detected at or above the reported quantitation limit and the decision to use the data is based on additional information.
- R - The sample result or analysis has been rejected due to serious deficiencies. The presence or absence of the analyte in the sample cannot be verified.

3.2 Downhole Video Surveys and Well Owner Questionnaires

3.2.1 Downhole Video Surveys

Downhole video surveys were conducted between October 6 and 10, 2014 in eight of the 13 study wells for which owner access was granted: LD02, PGDW05, PGDW20, PGDW23, PGDW41A, PGDW41B, PGDW44, and PGDW49 (**Table 3**). A video camera survey report for each of the aforementioned wells is included in **Appendix E**.

In general, wells were selected for the video survey based on the following criteria:

- Included in the 2014 sampling events
- Configured with an accessible wellhead (e.g., not in a pit or covered/obstructed by a permanent structure)
- Equipped with a minimum 1-inch-diameter access port or other larger opening, or,
- Equipped with a bolted sanitary well cap that could be removed for access to the casing without requiring disconnection of piping

Based upon the above criteria, downhole video surveys were not conducted in PGDW14, PGDW30, PGDW32, PGDW33, and PGDW45.

Downhole video surveys, including decontamination procedures, were conducted in general accordance with the SAP, QAPP, HASP, and SAP Addendum. The surveys were conducted by BESST, Inc., a subcontractor to AME.

The downhole video surveys were conducted in the selected wells to the extent practicable without removal of well pumps or other obstructions inside the well casing. At wells equipped with sanitary well caps, access for the video camera was assessed once the cap was removed. All equipment and wellheads were decontaminated prior to the work as described in the SAP Addendum.

Tools and equipment used to remove access port plugs and sanitary well caps were disinfected prior to use with a sodium hypochlorite solution. In addition, before access port plugs or sanitary well caps were removed, they were cleaned with an Alconox detergent wash and tap water rinse followed by saturation with a 1 percent solution of sodium hypochlorite. The video camera system and cable were decontaminated and disinfected prior to deployment into and upon

removal from boreholes using an Alconox detergent wash and distilled water rinse followed by saturation with a 1 percent solution of sodium hypochlorite.

Video surveys were performed by BESST using a GeoVision™ Nano Camera in conjunction with a nano rotating mirror. The video camera system is 0.75 inch in diameter and allowed for surveys of as much of the water-supply wells as possible without removing pumps or other equipment from the casing. Obstacles, including but not limited to pumps, wiring, and other pump- related equipment, limited the depth to which the camera system could be lowered in each of the wells except PGDW49. As a result, the depth to which the camera system was lowered in each well was determined by the WDEQ, in consultation with AME and BESST, based upon observations made prior to or during lowering of the camera system. The goal was to lower the camera system to the target depth or as deep as possible without endangering the camera system or pump and associated equipment. Video recording was performed under non-pumping and pumping conditions in wells that were equipped with a pump.

Two equipment blanks were obtained for laboratory analysis to check that contaminants were not introduced into the wells from the downhole video equipment. The first equipment blank was collected prior to conducting the video survey in the first well, PGDW49. The second sample was collected prior to conducting the video survey in PGDW23. The equipment blanks were analyzed for a select list of parameters specified by the WDEQ. Further details and laboratory analytical reports are included in **Appendix M**.

3.4.2 Well Owner Interviews

Interviews were conducted with the owners of PGDW05, PGDW14, PGDW23, PGDW30, PGDW32, PGDW33, PGDW41A, PGDW41B, PGDW44, PGDW45, and PGDW49 between October 6 and 9 and on November 3, 2014. The owner of LD02 and PGDW20 declined to be interviewed. The purpose of conducting the interviews was to collect information regarding well construction and integrity, maintenance histories, and other proximate and pertinent features (e.g., septic systems) that may relate to potential palatability and other concerns associated with water from the wells.

The completed well owner interview questionnaire for each of the aforementioned wells is included in **Appendix F**.

4. RESULTS OF 2014 GROUNDWATER INVESTIGATION WITH SUMMARY OF PRIOR SAMPLING RESULTS

4.1 Water-Supply Well Construction and Use

4.1.1 Water-Supply Well Construction and Condition

Of the 14 water-supply wells included in the study, permits were on file with the WSEO for six wells (Table 3). In the case of PGDW44, the WOGCC well integrity and pit reports associated the incorrect WSEO permit (24506) with PGDW44; the correct permit is 24508. The unusually large casing diameter (9 inches) and the well driller, Shell, as reported by the current owner, matched WSEO permit 24508. Also, the permit associated with PGDW23 in previous studies did not match the installation date and well details reported by the owner.

For seven of the water-supply wells, the results of the October 2014 video surveys provided further information on the construction and current condition of the wells (Table 3). Because the video surveys were performed without removing the pumps from the wells, the surveys generally did not proceed beneath the pump due to limited clearance, except for PGDW49. LD02 was not equipped with a pump, so the video survey extended to the current total depth of 398 ft, which is at the base of a collapsed section of casing.

The total depth of the water-supply wells ranges from 30 to 675 ft bgs (Table 3). Four of the wells (PGDW33, PGDW41B, PGDW45, and PGDW49) are less than 100 ft deep, one of the wells is greater than 500 ft (PGDW32, 675 ft), and the remaining nine are between 175 and 475 ft deep. As noted above, LD02 was originally drilled to 610 ft but has collapsed to 398 ft. The depth of the surface casing, or the minimum depth of the surface casing, is known for 10 of the water-supply wells, and ranges from 23 ft bgs in PGDW49 to 445 ft bgs in PGDW23. Information on the surface seal is not included in older WSEO well permit forms; however, four of the well permits indicate that a surface seal is present. At least two of the wells are completed as open boreholes beneath the surface casing: PGDW05 (open below 161.5 ft bgs) and PGDW32 (open below 500 ft bgs).

The permits for three of the water-supply wells include driller's logs. The apparent reported depth of unconsolidated deposits ranged from 3 to 25 ft: PGDW41B (3 ft of topsoil above shale), PGDW42 (25 ft of sand above shale, though "sand" appears synonymous with sandstone on the log), PGDW32 (3 ft of topsoil above sandstone). PGDW41B is screened adjacent to "gray sandy shale" and "gray shale." PGDW42 is screened adjacent to "sand." The driller's log as provided for PGDW32 ends above the screened interval.

4.1.2 Surrounding Land Use

At each of the 14 water-supply wells included in the study, the adjacent land use is agricultural, specifically irrigated cropland and/or livestock grazing (**Table 9**). Livestock (cows, horses, or

goats) have been corralled adjacent to or nearby most of the wells, with the exception of PGDW23, where the nearest corral is approximately 1,000 ft to the west.

Diesel and/or gasoline aboveground storage tanks (ASTs) are present on the properties near nine of the water-supply wells. Application of pesticides and/or herbicides on adjacent fields was noted, and in some cases, for control of weeds in landscaped areas.

Disposal of domestic waste is through septic systems, which were reportedly located at distances between 75 and 450 ft from water-supply wells currently or formerly used for domestic supply.

Other than gas wells and pits discussed earlier in the report, additional oil and gas related land use activities include cuttings disposal in a gully located approximately 200 ft west-northwest of PGDW23 and approximately 800 ft west-northwest of PGDW14, pipelines, and above ground tanks and other production related facilities.

4.1.3 Water-Supply Well Sample Representativeness

In accordance with the study's objectives, groundwater samples obtained in June and August 2014 were collected from water-supply wells; thus, the sampling results should be interpreted accordingly, with consideration of the differences between water-supply wells and monitoring wells. The differences arise from the purpose of the wells: Water-supply wells are usually installed with the intent of optimizing both the quantity and quality of the water produced, whereas monitoring wells are usually designed to characterize hydraulic head and/or groundwater chemical characteristics of a discrete permeable interval. Consequently, relative to monitoring wells, the characteristics of water-supply wells typically include the following: larger diameter, different construction materials, much more frequent pumping (with accompanying changes in hydraulic head and groundwater chemical characteristics), and screened or perforated intervals which may intersect multiple permeable intervals.

The construction and condition of the water-supply wells also bear consideration when interpreting the groundwater sampling results. These considerations include:

- LD02. During the October 2014 video survey, a collapsed section of casing was encountered at 398 ft bgs; whether the collapse constituted a complete or partial blockage could not be assessed. Furthermore, the well was not equipped with a pump, so grab samples were collected in June and August 2014. Consequently, the extent that the samples represented ambient groundwater versus stagnant water in the well casing is unknown.

- PGDW05, PGDW20, PGDW30, PGDW33, PGDW41A, and PGDW41B. As noted in Section 3, the sampling points for these wells were located downstream of the pressure tanks.

- PGDW20 and PGDW33. The sampling points for these wells were located at a distance from the well head. Well PGDW20 is approximately 250 ft from the hydrant sampling point and well PGDW33 is approximately 1,200 ft from the hydrant sampling point. The

total volume purged before collecting samples included an allowance for the estimated volume of the piping between the well and the sampling point.

4.2 Water-Supply Well Sampling

4.2.1 June and August 2014 Groundwater Sampling

This section includes results of depth-to-groundwater measurements, measurements of field water-quality parameters, and sampling of the water-supply wells by AME in June and August 2014. Sampling forms, including the recorded field water-quality parameters are in **Appendix N**. Copies of laboratory analytical reports are in **Appendix M**. Data validation reports are in **Appendix O.**

The headings of the tables that provide results for field water-quality parameters or laboratory analyses include drinking water standards and other comparison values. When not listed in a table, a corresponding drinking water standard or comparison value is not available. The drinking water standards and comparison values include:

- The EPA MCL is the greatest concentration of a constituent that is allowed in drinking water. MCL concentrations are set as low as is feasible using the best available analytical and treatment technologies and taking cost into consideration. MCLs are enforceable standards for public water supplies (US EPA, 2012).

- State of Wyoming Water Quality Rules and Regulations, Chapter 8, Quality Standards for Wyoming Groundwaters, Table 1, Class I Groundwater Quality (WY Class I Domestic). WY Class I Domestic standards apply to groundwater suitable for domestic use.

- State of Wyoming Action Level, Storage Tank Program (Wyoming Action Level). The Wyoming Action Levels are groundwater cleanup standards for GRO and DRO established by WDEQ VRP.

- The EPA DWEL is a drinking water lifetime exposure level, assuming 100 percent exposure from that medium, at which adverse, non-carcinogenic health effects would not be expected to occur (US EPA, 2012).

- State of Wyoming Drinking Water Equivalent Level (WY DWEL) for non-carcinogenic chemicals and Acceptable Drinking Water Levels (ADWL) for suspected and known carcinogenic chemicals, Voluntary Remediation Program. Values as published in Wyoming DEQ Factsheet 12E, December 2014 (WY DWEL). The WY DWEL is the maximum concentration of a constituent for which no known or anticipated adverse effects on human health will occur (WDEQ, 2014a). WY DWELs are calculated for chemicals for which no MCL is available.

- The EPA SDWR is a non-enforceable federal guideline regarding cosmetic effects (tooth or skin discoloration) or aesthetic effects (taste, odor, or color) of drinking water (US EPA, 2012).

- US EPA Drinking Water Advisory (EPA DWA). The EPA DWA is a non-regulatory concentration of a constituent in water that is likely to be without adverse effects on health and aesthetics for the period it is derived (US EPA, 2012a).

In the tables of laboratory analytical results, when the value of an analytical result is less than the method detection limit (MDL) or less than the reporting limit (RL), or in other words, it was not detected, then the value of the MDL or RL is listed after the "<" symbol. The MDL and RL are defined thus:

- MDL: The minimum concentration of a substance that can be measured and reported with 99 percent confidence that the analyte concentration is greater than zero; it is determined from analysis of a sample in a given matrix containing the analyte .

- RL: The RL is greater than the MDL. It is laboratory specific and is based on the expected use of the data. The RL is at a level where there is statistical confidence in the quantification of the sample concentration.

When the concentration of an analyte is between the MDL and the RL, there is confidence that the analyte is present but the exact concentration is not known; therefore, the laboratory flags concentrations reported between the MDL and RL as estimated using a "J" flag.

In the tables of measurements of field water-quality parameters and laboratory analytical results, when a reported concentration is greater than a drinking water standard or comparison value, the result value is highlighted with color and a special font or color alone, in accordance with notes in the tables. For consistency, when a reported laboratory analytical result is less than the MDL or RL and the MDL or RL is greater than a drinking water standard or comparison value, that result is also highlighted.

4.2.2 Previous Groundwater Sampling Events

This section includes tables that summarize the results from previous sampling events. These include individual sampling events from 1979 to 2006 plus a series of sampling events at PGDW05 from 2004 through 2008; they also include summary data from the US EPA Phase I to IV events of 2009 through 2011.

Previous sampling events from 1979 to 2008 include the following:

- LD02. By the well owner, following installation in 1994.

- PGDW05. On behalf of Tom Brown Inc. and Encana from September 2004 through October 2008. The October 2008 sampling was performed by AECOM, during which the

pump and discharge line were removed and replaced with a 2-inch submersible sampling pump.

- PGDW20. By the well owner, following purchase of the property in 1988, and subsequently in 1992 and 1993 after changes in water quality were observed. On behalf of Tom Brown, Inc. in 1997 and Encana in 2006.
- PGDW23. On behalf of Tom Brown Inc. in 2004.
- PGDW30. December 2007 by Inberg Miller Engineers, Inc. on behalf of Encana, with sample collection from a spigot near the residence.
- PGDW41B. On behalf of Tom Brown, Inc. in 2004.
- PGDW44. Following installation of the well in 1979, two sampling events were performed, and duplicate samples were collected on each event.

The sampling dates of water-supply wells for each US EPA project phase is as follows:

- Phase I: March 2009
- Phase II: January 2010
- Phase III: October 2010
- Phase IV: April 2011

The US EPA sampling events of March 2009 and January 2010 incorporated PGDW42, which was not sampled in 2014 because landowner access was not granted.

The US EPA reports do not recognize PGDW41A and PGDW41B as individual water-supply wells. For the January 2010 sampling event, the US EPA hired a local well service contractor to install a temporary pump and discharge line, because at the time, the water-supply well (singular) was inoperative. Based on similarities of the 2009 and 2010 sample results to the June and August 2014 results for PGDW41B, it is inferred the US EPA samples collected in 2009 and 2010 were obtained from PGDW41B. Samples collected by the US EPA in 2011 appear to represent a mixture of water from these two water-supply wells. PGDW41A and PGDW41B are connected to a common manifold, thus to sample each well individually, the pumps must be controlled by switching the power breakers on and off.

4.2.3 Groundwater Elevation

Depth to groundwater was measured during the June 2014 sampling event at 60F, LD02, PGDW32, PGDW45, and PGDW49 (**Table 10**). Depth to groundwater ranged from 10.1 (PGDW49) to 250.3 ft (PGDW32) below the measuring point (bmp). Approximate groundwater elevations ranged from 5,085.8 (PGDW32) to 5,360.2 ft NAVD88 (PGDW49). The observed range in water levels is attributable to the effect of pumping water-supply wells.

Depth to groundwater was measured during the August 2014 sampling event at LD02, PGDW32, PGDW44, PGDW45, and PGDW49 (**Table 10**). Depth to groundwater ranged from 10.3 (PGDW45) to 271.8 ft bmp (PGDW32). Approximate groundwater elevations ranged from 5,064.3 (PGDW32) to 5,355.6 ft NAVD88 (PGDW44). The observed range in water levels is attributable to the effect of pumping water-supply wells.

During the October 2014 video surveys, depth to groundwater was recorded for LD02, PGDW05, PGDW20, PGDW23, PGDW41A, PGDW41B, PGDW44, and PGDW49 (**Table 10**). Depth to groundwater ranged from 6.2 (PGDW49) to 197.5 ft bmp (PGDW23). Approximate groundwater elevations ranged from 5,162.3 (LD02) to 5,387.7 ft NAVD88 (PGDW41B).

Observed changes in groundwater elevation between June and August 2014 ranged from a decrease of 8.60 ft (PGDW49) to an increase of 15.50 ft (PGDW45). Over the same period the changes in groundwater elevation were smaller in 60F (0.20 ft increase) and LD02 (1.80 ft decrease). From August to October 2014, observed changes in groundwater elevation included a decrease of 14.70 ft (PGDW44) and increases of 3.80 ft (LD02) and 12.50 ft (PGDW49).

4.2.4 General Characteristics and Major Cations and Anions

4.2.4.1 Field Water-Quality Parameters

Field water-quality parameters measured during the supply-well sampling include dissolved oxygen, ferrous iron, oxidation-reduction potential, pH, salinity, specific conductance, temperature, and turbidity (**Table 11**). The parameter values listed are the final readings that were recorded immediately before sample collection commenced.

Measured dissolved oxygen concentrations ranged from -0.02 (PGDW20, June 2014) to 7.35 mg/L (PGDW41A, June 2014). The dissolved oxygen concentration of 7.35 mg/L was an apparent consequence of air entrainment when the water level was drawn down to the pump intake before sampling, and the dissolved oxygen value of -0.02 was an artifact of calibration. Otherwise dissolved oxygen concentrations ranged from 0.02 (PGDW41B, June 2014) to 4.29 mg/L (PGDW33, August 2014).

Measured ferrous iron concentrations ranged from 0 to 3.3 mg/L. Five of the 13 wells sampled had non-zero measurements of ferrous iron (LD02, PGDW31, PGDW41B, PGDW44, and PGDW49). The high value of 3.3 mg/L was measured in the August 2014 sample from PGDW44. Ferrous iron was detected at concentrations greater than the WY Class I Domestic standard of 0.3 mg/L during both sampling events in wells PGDW41B and PGDW44. No other wells had detections of ferrous iron greater that the WY Class I Domestic standard.

The oxidation-reduction potential measured in the samples ranged from -0.278 volts (PGDW44, August 2014) to +0.213 volts (PGDW33, August 2014).

The pH of all samples collected in June and August 2014 was greater than 7.00 (alkaline), and ranged from 7.01 (PGDW45, August 2014) to 9.97 (PGDW32, June 2014). The pH exceeded the

WY Class I Domestic standard and the EPA SDWR of 8.5 during both sampling events in the samples from PGDW05, PGDW20, PGDW23, PGDW30, and PGDW32.

The measured salinity ranged from 0.44 parts per thousand ($^0/_{00}$) (PGDW05, June 2014) to 4.5 $^0/_{00}$ (PGDW41A, August 2014), and the measured specific conductance ranged from 0.878 to 8.08 millisiemens per centimeter (mS/cm) in the same respective samples.

Groundwater temperature ranged from 8.65 degrees C (PGDW45, June 2014) to 24.2 degrees C (LD02, June 2014). The recorded temperature of 24.2 degrees C was affected by exposure of the grab sampling device to ambient conditions after sample collection but before the temperature was measured. Otherwise the upper recorded temperature was 17.1 degrees C (PGDW33, August 2014).

The measured turbidity of the groundwater samples ranged from -6.1 NTU (PGDW45, June 2014) to 59 NTU (PGDW41B, August 2014). Turbidity readings less than zero were artifacts of meter calibration (PGDW05, PGDW30, PGDW32, PGDW33, and PGDW45). The measured turbidity exceeded the WY Class I Domestic standard of 5 NTU during both sampling events in the samples from PGDW41B, the June 2014 samples collected from PGDW14 and PGDW44, and the August 2014 sample from PGDW49.

4.2.4.2 Major Cations, Major Anions, and Total Dissolved Solids

The groundwater samples collected in June 2014 and August 2014 were analyzed for major cations, major anions, and TDS. Cations were analyzed using both the total sample fraction (i.e. unfiltered) and the dissolved sample fraction (i.e. filtered in the field), with one exception (**Table 12A**). The turbidity of the samples from PGDW41B exceeded 20 NTU and thus were not analyzed for total (unfiltered) cations in accordance with the SAP.

The cations included in **Table 12A** are calcium, iron, magnesium, manganese, potassium, sodium, and strontium. Although iron and strontium are not traditionally identified as major cations, they are in the table because the concentration in some samples exceeded 1 mg/L. Manganese is included in the table because of its chemical similarity to iron. Anions in the table include alkalinity (various forms), bromide, chloride, fluoride, nitrate, nitrite, and sulfate. Nitrite and bromide, though not always identified as major anions, are included in the table with the other anions because the same analytical method was used for all anions.

The reported concentrations of total and dissolved sodium exceeded the EPA DWA of 20 mg/L (20 mg/L for individuals on a sodium-restricted diet, otherwise 30 to 60 mg/L) in all of the 2014 groundwater samples. Analytical results ranged from 79 mg/L (PGDW45, August 2014) to 1,400 mg/L (PGDW41A, June 2014). Reported iron concentrations were greater than the WY Class I Domestic and the EPA SDWR (both 0.3 mg/L) in the June 2014 dissolved samples from LD02 and PGDW05, both June and August dissolved samples from PGDW41B, and all samples taken from PGDW44. The maximum reported iron concentration was 3.7 mg/L in the August 2104 unfiltered (total) sample from PGDW44. Results for manganese were similar: reported concentrations exceeded the WY Class I Domestic and the EPA SDWR (both 0.05 mg/L) in the

June and the August 2014 unfiltered (total) sample from LD02, both June and August dissolved samples from PGDW41B, and all samples collected from PGDW44 and PGDW49.

Sulfate concentrations in all of the June and August 2014 groundwater samples exceeded the WY Class I Domestic standard and the EPA SDWR in all but one sample: the reported concentration in the sample collected from PGDW45 in August equaled the 250 mg/L standard. Reported sulfate concentrations ranged up to 3,500 mg/L in the sample collected from PGDW49 in June 2014. In both samples from PGDW41A in June and August 2014, concentrations of chloride (710 and 850 mg/L, respectively) exceeded the WY Class I Domestic standard and the EPA SDWR of 250 mg/L, and the concentrations of nitrate (21 and 17 mg/L, respectively) exceeded the EPA MCL and WY Class I Domestic standard of 10 mg/L.

In the groundwater samples collected in June and August 2014, the TDS concentration ranged from 560 mg/L (PGDW05, both samples) to 6,350 mg/L (PGDW41A, August 2014 sample); all concentrations were greater than the WY Class I Domestic standard and the EPA SDWR of 500 mg/L.

The groundwater samples collected between 1978 and 2008 were analyzed for a smaller set of cations and anions than in June and August 2014. Analysis for the samples collected from PGDW05 in 2008 also included orthophosphate and total suspended solids (**Table 12B**). In the samples obtained from PGDW05, the reported orthophosphate concentrations were less than the RL of 0.20 mg/L.

Results of the previous sampling at PGDW23, PGDW30, PGDW41B, and PGDW44 were similar to the results of the June and August 2014 sampling. In samples from PGDW05, reported concentrations of major cations, major anions, and TDS were generally consistent from 2004 to 2008; they were also consistent with concentrations reported in June and August 2014. Results of sampling from 1979 to 2008 were different from results of the June and August 2014 sampling for two of the wells:

- LD02. The reported sodium and sulfate concentrations (555 and 1,161 mg/L, respectively) reported in the sample collected in 1979 were less than the reported concentrations in the samples collected in June and August 2014 (630 to 730, and 1,700 mg/L respectively). However, TDS concentrations reported in 1979 were greater than those reported in 2014 (4,010 versus 2,500 to 2,560 mg/L, respectively, **Table 12A**). Differences may be attributable to the condition of LD02, which partially collapsed after the 1979 sampling event.

- PGDW20. When sampled in 1988, reported concentrations of sodium, sulfate, and TDS were 170, 250, and 532 mg/L respectively. After changes in water quality were observed, this well was resampled in 1992. Reported concentrations of sodium, sulfate, and TDS increased to 1,100, 3,000, and 4,600 mg/L, respectively. Results from another sampling event in 1993 were similar. Reported results for a sample obtained in 1997 were anomalous, in that the reported sulfate concentration of 4,630 mg/L exceeded the reported TDS concentration of 3,950 mg/L (**Table 12B**). Relative to the sampling results

from 1992 and 1993, concentrations of sodium, sulfate, and TDS declined by June and August 2014 to 520 to 600, 1,300, and approximately 2,000 mg/L, respectively (**Table 12A**).

The groundwater samples collected by the US EPA from 2009 through 2011 were analyzed for a smaller set of major cations and major anions. For samples obtained in 2009 and 2010, cations apparently were analyzed for the total sample fraction (i.e. not filtered in the field), since the reports referenced analytical methods for "total metals", whereas samples obtained in 2011 for analysis of cations were filtered. The major cations included calcium, magnesium, potassium, and sodium, plus iron and manganese for some of the samples. Anions included alkalinity (as CaCO3), chloride, fluoride, nitrate, nitrite, and sulfate (**Table 12C**). The US EPA Phase I report (March 2009 samples) lists the incorrect units in Table 12, anions; this has been corrected herein.

Results for the samples collected in 2009 through 2011 were generally similar to the results of the 2014 sampling, in that the reported concentration of sodium exceeded the EPA DWA of 20 mg/L in all samples, and the reported concentration of sulfate exceeded the WY Class I Domestic standard and the EPA SDWR in all samples except one from PGDW45 (**Table 12C**). Some of the reported iron and manganese concentrations from samples collected in 2009 and 2010 are attributable to turbidity, particularly 11.4 mg/L of iron in the sample from PGDW49 in January 2010.

4.2.4.3 General Chemistry

General chemistry analyses for the samples collected in June and August 2014 included ammonia, cyanide, dissolved organic carbon (DOC), sulfide, surfactants, and total organic carbon (TOC) (**Table 13A**). Reported concentrations of ammonia and cyanide in all samples were less than the respective drinking water standards or comparison values, and reported concentrations of surfactants were less than the RL. Reported concentrations of DOC and TOC ranged up to 6.2 and 6.1 mg/L in the June 2014 and August 2014 samples collected from PGDW49, respectively. Reported sulfide concentrations ranged from less than the RL to 90 mg/L estimated, low bias (J-) in the sample collected from PGDW32 in June 2014.

General chemistry analyses for samples obtained between 2004 and 2008 from PGDW05 included specific conductance, pH, ammonia, sulfide, surfactants, TOC, and total Kjeldahl nitrogen (**Table 13B**). The reported pH was alkaline and ranged from 9.0 to 9.30, which exceeded the WY Class I Domestic standard and the EPA SDWR of 8.5. Reported concentrations of ammonia, sulfide, surfactants, and total Kjeldahl nitrogen were less than the respective RLs. In the samples designated deep and shallow, the reported TOC concentrations were 1.2 and 1.0 mg/L, respectively. In the groundwater sample collected from PGDW23 in 2004, cyanide was reported at a concentration of less than the RL. In the sample collected from PGDW41B in 2004, ammonia was reported at 0.28 mg/L, and sulfide was reported at less than the RL.

The groundwater samples collected by the US EPA in March 2009 were analyzed for cyanide (**Table 13C**). Reported concentrations of cyanide were less than the respective drinking water standards or comparison values.

4.2.5 Trace Metals

Groundwater samples collected in June and August 2014 were analyzed for trace metals using both the total sample fraction (i.e. unfiltered) and the dissolved sample fraction (i.e. filtered in the field), except for PGDW41B (**Table 14A**). The turbidity of the samples from PGDW41B exceeded 20 NTU and thus they were not analyzed in accordance with the SAP.

Reported concentrations of five metals were greater than drinking water standards or comparison values in samples obtained in June and August 2014:

- Total aluminum concentrations were greater than the EPA SDWR of 50 µg/L in June 2014 samples collected from PGDW32 (duplicate sample, 61 J µg/L) and PGDW44 (74 J µg/L). In five other samples, the result was qualified as not detected (U) at a concentration less than the RL of 100 µg/L due to the presence of aluminum in the method blank.

- Total arsenic concentrations were greater than the EPA MCL of 10 µg/L in the samples from PGDW41A (13 and 11 µg/L, June and August 2014, respectively) and the sample collected in June 2014 from PGDW49 (11 µg/L). All reported dissolved arsenic concentrations were less than the EPA MCL.

- Lithium concentrations were greater than the WY DWEL of 66.7 µg/L in the June and August 2014 total and dissolved samples collected from PGDW41A, PGDW44, and PGDW49, the June 2014 total and dissolved samples from PGDW41B, and the August dissolved samples from LD02 and PGDW41B. Lithium results ranged from 21.5 µg/L (PGDW05, total, June 2014) up to 112 µg/L (PGDW41B, dissolved, August 2014).

- Thallium concentrations were greater than the EPA MCL of 2.0 µg/L in the June 2014 dissolved samples from wells PGDW14, PGDW44, and PGDW45, the August dissolved samples from PGDW44 and PGDW49, and the August total samples from PGDW41A and PGDW49. Reported concentrations ranged from non-detect (<2.0 µg/L) up to 3.3 J µg/L (PGDW14, June 2014).

- Uranium concentrations exceeded the EPA MCL of 30 µg/L in the June and August 2014 total and dissolved samples from PGDW33, PGDW41A, and PGDW49, and the June 2014 total and dissolved samples from PGDW45. Reported concentrations ranged from non-detect (<0.067 µg/L) up to 265 µg/L (PGDW41A, dissolved, August 2014). In addition the reported uranium concentrations in the August 2014 total and dissolved samples from PGDW45 were greater than the EPA DWEL of 20 µg/L.

The groundwater samples collected from PGDW05 in September 2004, September 2007, and October 2008 were analyzed for 13 to 18 trace metals, including phosphorus (**Table 14B**). The reported trace metal concentrations were either less than the RL or less than drinking water standards or comparison values. Results were reported to the RL rather than the MDL, and the RLs for aluminum, arsenic (2008 only), cadmium (2007 and 2008), lead, and selenium (2008)

were greater than some of the respective drinking water standards or comparison values. The groundwater samples obtained from PGDW23 and PGDW41B in 2004 were analyzed for a subset of trace metals, including phosphorus. The reported concentrations were either less than the RL or less than drinking water standards or comparison values. The RL for lead in the sample from PGDW41B was greater than the Wyoming Class 1 Domestic standard.

The groundwater samples collected by the US EPA from 2009 through 2011 were analyzed for 17 trace metals using the total sample fraction (i.e. unfiltered). Compared with the analysis of samples from June and August 2014, the analysis conducted by the US EPA did not include boron, lithium, molybdenum, and uranium (**Table 14C**). Reported aluminum concentrations were greater than the EPA SDWR of 50 µg/L in the March 2009 samples from PGDW30, PGDW32, and PGDW33 (76 J, 54.1 J, and 51.2 J µg/L, respectively), and the January 2010 samples from PGDW49 (81.8 J µg/L) and PGDW41B (741 µg/L). In other samples, the results for aluminum were qualified as not detected (U) at a concentration less than the RL of 200 µg/L. Lead was reported in the PGDW41B sample at a reported concentration of 38.3 µg/L, which exceeded the WY Class I Domestic standard of 15 µg/L. The reported aluminum and lead concentrations in the PGDW41B sample appear to be affected by sample turbidity, because the reported aluminum concentration is greater than the theoretical solubility in neutral to alkaline groundwater (Hem, 1986).

4.2.6 Petroleum Constituents and Organic Compounds

4.2.6.1 Petroleum Constituents

Groundwater samples collected in June and August 2014 were analyzed for DRO, GRO, and hydrocarbon oil and grease (**Table 15**). DRO analyses were performed on two sample aliquots: one that was prepared using silica gel clean-up (SGCU) and one that was prepared without using SGCU. Reported concentrations of DRO and GRO were less than the respective Wyoming Action Levels.

Petroleum hydrocarbons such as DRO and GRO are a mixture of hundreds to thousands of individual compounds. Due to effective solubility differences, however, only a subset of these compounds is dissolved in groundwater at measurable concentrations. Fresh petroleum fuels such as DRO and GRO consist of non-polar compounds, which are compounds that have a high affinity for oil and a low affinity for water. However, biodegradation of petroleum compounds in the environment produces polar metabolites, such as organic acids, esters, alcohols, aldehydes, phenols, and ketones. Polar compounds have a high affinity for water and a lower affinity for oil.

Analyses for DRO and GRO are non-specific. That is, the methods report all organic compounds that are extracted from the sample (by a solvent for DRO analysis, carrier gas for GRO analysis), that pass through the analytical instrument's chromatographic column within the same time range as GRO and DRO, and are registered by the instrument's detector. Thus, in addition to dissolved petroleum constituents, the methods will also report as DRO or GRO constituents such as petroleum biodegradation products, other chemicals (including chlorinated solvents), naturally occurring dissolved organic matter, and laboratory artifacts.

Silica gel clean-up (SGCU) is a method of removing polar organic compounds from the sample while retaining the non-polar hydrocarbons. Thus, analytical results for DRO with SGCU represent the concentration of non-polar hydrocarbons, and are more representative of petroleum hydrocarbons. WDEQ Solid and Hazardous Waste Division, Storage Tank Program Guidance #7 provides more information on the use of SGCU for DRO analyses (WDEQ, 2014b). An additional reference on SGCU methodology is Zemo et al., 2013.

In groundwater samples prepared without SGCU, DRO concentrations ranged from less than the MDL (0.016 mg/L) to 0.25 J mg/L (PGDW41B, August 2014). Some samples were qualified as not detected (U) at a concentration less than the RL of 0.049 to 0.051 mg/L as a result of data validation. Concentrations of DRO were reported greater than MDL in at least one June or August 2014 sample collected from 10 of the 13 wells. All DRO results with reported concentrations greater than the RL (0.049 to 0.051 mg/L) were qualified by the laboratory as exhibiting a chromatographic pattern which did not resemble the diesel standard (Y). These results were subsequently qualified as estimated (J) during data validation: LD02 (June 2014), PGDW05 (August 2014), PGDW30 (August 2014), PGDW41A (June 2014), PGDW41B (both), and PGDW49 (June 2014). DRO without SGCU was not detected in any 2014 samples greater than the Wyoming Action Level of 1.0 mg/L.

Concentrations of DRO in samples prepared with SGCU ranged from less than the MDL (0.016 mg/L) up to 0.23 J mg/L (PGDW41B, August 2014). DRO concentrations were greater than the MDL in samples collected from four of the 13 water-supply wells: PGDW05 (both), PGDW30 (June 2014), PGDW41B (both), and PGDW45 (June 2014, but not the duplicate sample). Concentrations greater than the RL (0.049 to 0.051 µg/L) were reported in both 2014 samples from PGDW41B; these results were qualified by the laboratory as exhibiting a chromatographic pattern which did not resemble the diesel standard (Y) and were subsequently qualified as estimated (J) during data validation. DRO with SGCU was not detected in any 2014 sample greater than the Wyoming Action Level of 1.0 mg/L.

In all but three of the June and August 2014 groundwater samples, reported GRO concentrations were either less than the MDL (0.0057 to 0.013 mg/L), or were qualified as not detected (U) at a concentration greater than the RL (0.05 mg/L) as a result of data validation. The reported GRO concentration was greater than the MDL in the June 2014 sample collected from PGDW05 (0.15 J mg/L) and in the June 2014 primary and duplicate samples collected from PGDW45 (0.018 J and 0.025 J, respectively). Only one sample result (PGDW05, June 2014) had a reported GRO concentration greater than the RL (0.05 mg/L); this result was qualified by the laboratory as exhibiting a chromatographic pattern which did not resemble the gasoline standard (Y) and was subsequently qualified as estimated (J) during data validation. GRO was not detected in any sample greater than the Wyoming Action Level of 6.6 mg/L.

Reported concentrations of hydrocarbon oil and grease were all less than the RL (4.72 to 5.45 mg/L) for samples collected in June and August 2014.

4.2.6.2 Volatile Organic Compounds by Gas Chromatography/ Mass Spectrometry

Reported concentrations of most VOCs were less than the MDL in the groundwater samples collected in June and August 2014 (**Tables 16A** and **16B**). Seven VOCs were reported at concentrations greater than the MDL in at least one sample: 2-propanol, acetone, carbon disulfide, isopropyl benzene, methylene chloride, naphthalene, and tert-butyl alcohol (TBA). The reported concentrations of these compounds were all less than drinking water standards or comparison values.

Acetone and methylene chloride are known as common laboratory contaminants (US EPA, 1991). June and August 2014 trip blank samples had reported concentrations of 2-propanol (isopropyl alcohol) greater than the MDL in 15 of 20 trip blank samples. Acetone and 2-propanol were qualified as not detected (U) in groundwater samples when the same compound was reported in the associated trip blank. Reported concentrations greater than the MDL may be artifacts of laboratory analysis. A potential indication of this is that June 2014 reported concentrations of acetone, methylene chloride, and 2-propanol greater than the MDL were all qualified as estimated (J or J-), while these compounds were not reported in any of the August 2014 samples. In two instances, 2-propanol was reported in the June 2014 duplicate samples, but not the primary samples.

The analysis of the June and August 2014 groundwater samples included reporting of TICs (**Table 16C**). One TIC was reported in a single sample: tert-butyl iodide (5.3 J µg/L) collected from PGDW05 in June 2014.

4.2.6.3 Glycols

The groundwater samples collected in June 2014 were analyzed for 2-butoxyethanol, diethylene glycol, tetraethylene glycol, and triethylene glycol in accordance with the SAP. Subsequently, the subcontract laboratory analyzed groundwater samples collected in August 2014 for glycols using their standard target compound list (ethylene glycol and propylene glycol) instead of the four glycols listed in the SAP (**Table 17**). Reported concentrations of glycols in all samples were less than the respective MDLs, with the exception of 2-butoxyethanol (3.1 J mg/L) in the June 2014 sample collected from PGDW33.

4.2.6.4 Volatile Organic Acids

Reported concentrations of volatile organic acids were less than the respective MDLs in all June and August 2014 groundwater samples, with the exception of pyruvic acid (2,060 µg/L) in the August 2014 sample collected from LD02. (**Table 18**).

4.2.6.5 Semivolatile Organic Compounds by Gas Chromatography/ Mass Spectrometry and Acrylamide

Reported concentrations of most SVOCs were less than the MDL in the groundwater samples collected in June and August 2014 (**Tables 19A** and **19B**). Two SVOCs, bis(2-ethylhexyl) phthalate and butyl benzyl phthalate, were reported at concentrations greater than the MDL (1.6

µg/L and 0.97 µg/L respectively). Bis(2-ethylhexyl) phthalate was reported at concentrations greater than the MCL (6 µg/L) in samples from five water-supply wells: PGDW05 (17 ug/L, June 2014), PGDW23 (6.9 J µg/L, August 2014 duplicate sample only), PGDW30 (6.7 J µg/L, August 2014), PGDW41A (12 µg/L, June 2014), and PGDW44 (6.4 J and 9.9 µg/L, June and August 2014, respectively). Butyl benzyl phthalate was reported at a concentration of 18 µg/L in the August 2014 sample from PGDW05; the reported concentration was less than the WY DWEL of 6,670 µg/L.

Bis(2-ethylhexyl) phthalate [aka di(2-ethylhexyl) phthalate] is used as a plasticizer in flexible PVC plastics (ATSDR, 2010, Budavari, 1996). Phthalates are also common laboratory contaminants at concentrations less than 100 µg/L (US EPA, 2014). For each of the four pairs of primary and duplicate samples, the reported concentration of one of the sample pairs was less than the MDL, while the other was greater than the MDL. In other cases, when bis(2-ethylhexyl) phthalate was reported at a concentration greater than the MDL in either the June or August 2014 sample, it was reported at less than the MDL in the other sample. This suggests that some of the reported concentrations of bis(2-ethylhexyl) phthalate may be an artifact of laboratory analysis, or may be associated with the materials used to plumb the wells and distribution piping, particularly those where the sampling point was downstream of the pressure tanks (PGDW05, PGDW20, PGDW30, PGDW41A, and PGDW41B).

The analysis of the June and August 2014 groundwater samples included reporting of TICs (**Table 19C**). TICs were reported in the following samples:

- LD02, August 2014: Unknown compound, 37 J µg/L.
- PGDW05, June 2014: Z-9-Octadecenamide, 6.7 J µg/L.
- PGDW20, June 2014: Unknown compound, 4.9 J µg/L.
- PGDW20, August 2014: 2-[2-[4-(1,1,3,3-tetramethylbutyl)phenoxy]ethoxy]-ethanol, 18 J µg/L; Heneicosane, 4 J µg/L; p-tert-Amyl phenoxy ethanol, 10 J µg/L; and 6 unknown compounds at concentrations ranging from 6 J to 180 J µg/L.
- PGDW41A, August 2014: Unknown compound, 4.4 J µg/L.
- PGDW41B, June 2014: Two unknown compounds, 6.4 J and 4.2 J µg/L.
- PGDW41B, August 2014: Unknown compound, 9.2 J µg/L.

4.2.6.6 Pesticides

Pesticides were analyzed by three different analytical methods and included three classes of target analytes: nitrogen and phosphorous-containing pesticides (**Table 20**), organochlorine pesticides (**Table 21**), and organophosphorus pesticides (**Table 22**). Reported concentrations of nitrogen and phosphorous-containing pesticides, and organophosphorus pesticides were less than the respective MDLs in all groundwater samples collected in June and August 2014.

Three organochlorine pesticides were detected greater than the MDL: beta-BHC, Endosulfan II, and gamma-BHC (Lindane). The organochlorine pesticide beta-BHC was reported in the August 2014 sample from PGDW23 at a concentration of 0.06 J µg/L, which was greater than the WY DWEL of 0.0499 µg/L (**Table 21**). Endosulfan II was detected in two samples and gamma-BHC was detected in six samples. Reported concentrations of Lindane were less than the EPA MCL of 0.2 µg/L. There are no comparison values for Endosulfan II.

4.2.7 Dissolved Gases

Analyses for dissolved gas concentrations in June and August 2014 groundwater samples included ethane, ethene, methane, and propane. Ethane and methane were analyzed by two methods: RSK-175 and GC-NOS (**Table 23A**).

Results obtained by method GC-NOS were qualified as estimated, project management decision on use of data (JP or J/PM in the data validation report); or, compound not detected, project management decision on use of data (UP or U/PM in the data validation reports). The results analyzed by method GC-NOS were qualified because the data validation reviewer was able to perform only a partial reconstruction of the results based on the data supplied by the laboratory. Ethane and methane results analyzed by GC-NOS are in general agreement with ethane and methane results analyzed by RSK-175, which supports use of the GC-NOS data.

Reported methane concentrations ranged from less than the MDL (1 to 5 µg/L, method RSK-175) or less than the RL (0.2 µg/L, method GC-NOS) to between 1,100 µg/L (method RSK-175) and 1,300 µg/L JP (method GC-NOS) in the sample collected from PGDW30 in August 2014. All reported methane concentrations were less than the WOGCC notification level for water sources of 10,000 µg/L.

The analysis of the June and August 2014 groundwater samples by method GC-NOS included dissolved gas composition in terms of mole percent (**Table 23B**). Reported nitrogen mole percentages ranged from approximately 74 to 90, carbon dioxide mole percentages ranged from approximately 0 to 8, oxygen mole percentages ranged from approximately 8 to 17, and argon mole percentages ranged from 0.96 JP to 1.62 JP. The greatest reported methane concentration was 4.09 JP mole percent in the sample collected from PGDW30 in June 2014.

4.2.8 Organic Analytes, Summary of Detections

Table 24A is a summary of the detections of organic compounds in the samples collected in June and August 2014; results are shown only where the reported concentration was greater than the MDL. The table does not include TICs. Analytes reported at concentrations greater than the MDL or RL in at least one of the samples include: two petroleum hydrocarbons DRO (includes samples prepared with and without SGCU) and GRO, 14 organic compounds of which half are VOCs and three dissolved gases.

Table 24B is a summary of the detections of organic compounds in the groundwater samples collected from 2004 through 2008. Results are shown only where the reported concentration was greater than the MDL or RL. Only well PGDW05 had detections of organic compounds during

this time period. In the sample from PGDW05 in November 2007, DRO, total extractable hydrocarbons, and total purgeable hydrocarbons were reported at concentrations of 1,600, 3,300, and 25 µg/L, respectively; however, reported DRO concentrations in prior and subsequent samples were less than the MDL. Similarly, bis(2-ethylhexyl) phthalate was reported at a concentration of 36 µg/L in a sample from 2005 but not in seven samples collected at later dates. Two glycols were reported in the October 2007 sample from PGDW05; however, one was also present in a field blank, and neither was confirmed in a sample collected in November 2007. Organic compounds reported above the MDL in the samples collected from PGDW05 in December 2008 include acetone, methylene chloride, and methane. The December 2008 concentrations of acetone and methylene chloride were less than drinking water standards or comparison values; these compounds are also common laboratory contaminants.

Table 24C is a summary of the detections of organic compounds in the groundwater samples collected by the US EPA from 2009 through 2010; results are shown only where the reported concentration was greater than the MDL or RL. The table is derived from summary tables in the US EPA Phase I and Phase II reports. Bis(2-ethylhexyl) phthalate was reported at concentrations greater than the MCL of 6 µg/L in three samples: March 2009 from PGDW14 (12 ug/L), March 2009 from PGDW20 (6.4 µg/L), and the January 2010 blended sample from PGDW41A and PGDW41B (11 and 7.4 J µg/L, analyses from two separate laboratories).

Reported concentrations of other organic compounds in samples collected in 2009 and 2010 were less than respective drinking water standards or comparison values (Table 24C). Analytes reported at concentrations greater than the MDL in at least one of the samples include three petroleum hydrocarbons: DRO (includes samples prepared with and without SGCU); GRO (including total purgeable hydrocarbons) and total extractable hydrocarbons. Additionally, 27 organic compounds of which 6 are VOCs and 17 are SVOCs and two dissolved gases were also reported.

4.2.9 Radiochemistry

Radiochemistry analyses for the June and August 2014 samples included gross alpha, radium-226, radium-228, radon-22, and strontium-90 (**Table 25**). For comparison with the WY Class I Domestic standards, the table includes the sum of radium-226 plus radium-228 and an estimate of gross alpha activity excluding uranium.

Gross alpha results were qualified JP or UP (J/PM or U/PM in the data validation reports) because the WY Class I Domestic standard is "Gross alpha particle radioactivity (including radium- 226 but excluding radon and uranium)," whereas the EPA MCL applies to gross alpha radioactivity without qualifications. The analytical laboratory results were provided as gross alpha, which included uranium but did exclude radon due to the analytical methodology. Gross alpha activity in the groundwater samples collected in June and August 2014 ranged from less than the MDL of between 2.58 and 9.55 picocuries per liter (pCi/L) to 168 JP pCi/L in the June 2014 sample from PGDW41A. Reported gross alpha activity exceeded the EPA MCL of 15 pCi/L in the samples obtained in June and August 2014 from PGDW14, PGDW33, and PGDW41A and the sample collected in June 2014 from PGDW49.

In the samples obtained in June and August 2014, the reported radon activity ranged from less than the MDL (63.4 UJ to 174 UJ pCi/L) to 1,350 J pCi/L (PGDW41A, June 2014). Reported radon activity exceeded the EPA MCL of 300 pCi/L in the samples collected in June and August 2014 from PGDW14, PGDW23, PGDW32, PGDW41A, PGDW44, PGDW45, and PGDW49 and the sample collected in June 2014 from PGDW33.

Strontium-90 results were qualified as UP (U/PM in the data validation reports) because the analytical method employed by the laboratory did not differentiate strontium-90 from other radioactive isotopes of strontium. Nonetheless, the reported activity of strontium-90 in all samples was less than the MDL.

The total radium-226 plus radium-228 activity (i.e. the sum of the activity of the two isotopes) in the June and August 2014 groundwater samples ranged from less than the MDL (i.e. less than the MDL for both isotopes) to 5.62 and 6.17 pCi/l in the samples from PGDW41B. The reported activity in the samples from PGDW41B exceeded the WY Class I Domestic standard of 5 pCi/L.

The gross alpha activity excluding uranium may be estimated from the dissolved uranium concentration. Uranium concentration data from **Table 14A** are listed in **Table 25** with the calculated gross alpha activity excluding uranium. The formula for this calculation is provided in footnote 3 of **Table 25**. The estimated gross alpha readings ranged from ND up to 9.14 pCi/L in the sample collected from PGDW49 in June 2014. This is less than the WY Class I Domestic standard of 15 pCi/l.

4.2.10 Microorganisms

The June and August 2014 groundwater samples included quantification of E.coli and total coliform counts, and screening tests for iron-related bacteria and sulfate-reducing bacteria (**Table 26A**). Reported E.coli counts were less than the MDL of 1 colony-forming unit per 100 milliliters (cfu/100 ml), except for 1 cfu/100 ml in the June sample collected from LD02.

Reported total coliform results ranged from less than the MDL of 1 cfu/100 ml to a high of 370 cfu/100 ml in the June 2014 sample from well LD02. Well PGDW23 had reported levels of total coliform of 3 and 5 cfu/100 ml in the August primary and duplicate samples. Well PGDW32 also had a detection of total coliform in the August sample of 32 cfu/100 ml. Because these two wells had coliform detections above the MDLs, and the water was being used for household uses, the WDEQ performed another separate sampling in September 2014 to confirm the total coliform detections and to test to make sure there was no fecal coliform present. Well PGDW23 had a confirmation sample result of 35 cfu/100 ml, but no fecal coliform was reported (<1 cfu/100 ml). Well PGDW32 reported <1 cfu/100 ml for total and fecal coliforms. These results were shared with the well owners and measures to clean their respective wells were discussed.

June 2014 results for wells PGDW33 (14 cfu/100 ml) and PGDW44 (5 cfu/100 ml) were above the MDL, however the follow-up August sampling at these two wells did not confirm the presence of total coliform and no further sampling was performed. Note well LD02 (no pump) (1 cfu/100 ml E. coli and 370 cfu/100 ml total coliform, June 2014) and well PGDW45 (stock well)

(5 cfu/100 ml total coliform, August 2014) are not used as household wells and therefore no confirmation sampling was performed.

Iron-related bacteria were reported in both the June and August 2014 samples from LD02, PGDW14, PGDW41B, PGDW44, and PGDW49. Iron-related bacteria were not reported in the August 2014 duplicate sample from PGDW49. Iron-related bacteria were reported in one 2014 sample from PGDW05 (August), PGDW32 (August), PGDW33 (June), PGDW41A (August), and PGDW45 (June 2014 duplicate sample). The greatest reported iron bacterial counts were 230,000 cfu/100 ml in each of the samples collected in August 2014 from PGDW41A and PGDW41B.

Sulfate-reducing bacteria were reported in both the June and August 2014 samples collected from PGDW44. Bacteria were reported in one sample from PGDW30 (August), PGDW32 (August), PGDW33 (June), PGDW41A (August), PGDW41B (June), and PGDW49 (August 2014). Sulfate-reducing bacteria were not reported in the August 2014 duplicate sample from PGDW49. The greatest reported bacterial counts were 120,000 J cfu/ml in the sample collected in June 2014 from PGDW33 and the sample collected in June 2014 from PGDW44.

The groundwater samples collected from PGDW05 in October 2008 were analyzed for iron-reducing bacteria, slime-forming bacteria, and sulfate-reducing bacteria. The presence/absence of total coliform was reported for the purge sample (**Table 26B**). Reported counts for the three bacteria were: 1,400,0000, 1,250,000, and 120,000 cfu/100 ml for iron-related bacteria, slime-forming bacteria, and sulfate-reducing bacteria, respectively. Total coliform was reported as present in the purge sample. Samples collected from PGDW05 during earlier sampling events in 2005 to 2007 were analyzed for a varying set of microbial parameters. In these samples, reported bacterial counts for E.coli and total coliform were less than the RL, and reported counts of iron-related bacteria, sulfate reducing bacteria, and heterotophic bacteria ranged up to 260,000, 500,000, and 140,000 CFU/100 ml, respectively.

In samples collected from PGDW20 (1988 to 2006) and PGDW23 (2004), total coliform was reported as absent, or less than the reporting limit of 1 maximum probable number per 100 milliliters (MPN/100 ml).

For the groundwater samples collected by the US EPA in 2009 and 2010, analyses for microorganisms included heterotrophic bacteria, iron-related bacteria, and sulfate-reducing bacteria (**Table 26C**). Reported heterotrophic bacteria counts ranged from less than the MDL of 200 MPN/100 ml to 51,000 MPN/100 ml in the sample collected in January 2010 from PGDW23. The greatest iron-related and sulfate-reducing bacterial counts were reported in the sample obtained from PGDW49 in January 2010, and were 3,600,000 and a range of 1,000,0000 to 10,000,0000 cfu/ml, respectively.

4.2.11 Stable Isotopes

Stable isotope analyses of the groundwater samples collected in June and August 2014 included carbon-13 in dissolved inorganic carbon (DIC), carbon-13 in methane, nitrogen-15 in nitrate, oxygen-18 in nitrate, and deuterium in methane (**Table 27**). Results are given in relative

difference, or del (δ) in parts per thousand ($^{0}/_{00}$) versus a reference standard. No results are provided when DIC, methane, or nitrate concentrations were too low to perform the isotopic analysis.

4.2.12 Quality Assurance/ Quality Control Samples

Quality assurance/quality control samples collected during the June and August 2014 samples included field blanks and trip blanks (**Table 28**). The table is a summary of the detections of analytes; results are shown only where the reported concentration was greater than the method detection limit.

Common laboratory contaminants that were reported at concentrations greater than the MDL in the trip blank samples include acetone, 2-butanone, methylene chloride, and toluene (US EPA, 1991). Phthalates are also common laboratory contaminants at concentrations less than 100 µg/L (US EPA, 2014.) Another compound frequently reported at concentrations greater than the MDL in the trip blank samples is 2-propanol (isopropyl alcohol) in 15 of 20 trip blank samples.

4.3 Data Validation and Reporting

Data validation reports prepared by Veridian are in **Appendix O**. Analytical results reviewed in the data validation were within project criteria and thus were acceptable for use or acceptable for use with qualification (e.g. estimated concentration, "J"). Eight results were rejected out of 11,714 total results.

4.3.1 Major Cations and Ions and General Chemistry

Some of the sample containers for the June 2014 sample collected from PGDW30 were delayed in shipping and arrived at the laboratory outside of temperature criteria; results for nitrate, nitrite, and methylene blue active substances (MBAS) for this sample were rejected because they were analyzed outside of holding time requirements (**Tables 12A and 13A**).

Other qualifier flags were assigned due to continuing calibration blank, method blank, laboratory control sample (LCS), and MS/MSD samples falling outside of project acceptance criteria. Field duplicate samples were within acceptable criteria except for one pair of cyanide results, one pair of the ammonia results, and two pairs of sulfide results; the associated results were qualified as estimated (UJ or J).

Sulfide results were qualified as estimated (UJ) or estimated with a potential low bias (J-) because the samples were unpreserved (**Table 13A**).

4.3.2 Trace Metals

One of four sample coolers holding a portion of the samples collected on August 21, 2014 (SDG 260131) was delayed in shipping and arrived at the laboratory outside of temperature criteria. Results for the sample collected from PGDW20 were qualified as estimated (UJ or J-, **Table 14**). One dissolved lead result (PGDW49, June 2014) was rejected due to a MS/MSD out of

acceptance criteria. The remaining qualifiers were assigned due to continuing calibration verification (CCV), method blank, MS/MSD, serial dilution, and post-digestion spike (PDS) analyses falling outside of control criteria. Field duplicate samples submitted were within acceptance criteria, except for four field duplicate pairs; the associated sample results were qualified as estimated (J).

4.3.3 Petroleum Constituents and Organic Compounds

One of four coolers holding a portion of the samples collected on August 21, 2014 (SDG 260131) was delayed in shipping and arrived at the laboratory outside of temperature criteria; the associated results listed below were qualified as estimated (UJ or J-):

- LD02: GRO and volatile organic compounds (**Table 15**)
- PGDW20: GRO, volatile organic compounds, glycols, volatile organic acids, organochlorine pesticides, nitrogen and phosphorous pesticides, and organophosphorous pesticides analyses (**Table 15**).
- TB-1: GRO and VOCs (**Table 28**).

4.3.3.1 Petroleum Constituents

Fourteen results for DRO or GRO analyses were qualified by the laboratory as exhibiting a chromatographic pattern which did not resemble diesel or gasoline standards (Y). These results were qualified as estimated (J) during data validation, and include samples collected from LD02 (June 2014), PGDW05 (both samples from 2014), PGDW30 (August 2014), PGDW41A (both samples from 2014), PGDW41B (both samples from 2014), PGDW44 (August 2014), and PGDW49 (June 2014), (**Table 15**). GRO results for the field duplicate pair collected from PGDW45 in June 2014 were qualified as estimated (J) due to relative percent differences (RPD) above acceptance criteria. Some results for DRO and GRO were qualified as not detected (U) due to reported concentrations in the associated method blank or trip blank samples.

4.3.3.2 Volatile Organic Compounds by Gas Chromatography/ Mass Spectrometry

The containers for the samples collected from PGDW44 in June 2014 contained bubbles; the associated sample results were qualified as estimated (UJ or J-) (**Tables 16A** and **16B**). Four acetone results, one chloroform result, and ten 2-propanol results were qualified as not detected (U) due to reported concentrations in the associated method blank or trip blank samples. Field duplicate samples were within acceptance criteria, except for one pair of 2-propanol results, which were qualified as estimated (J). The remaining qualifiers (UJ) were assigned due to continuing CCV and initial calibration verification (ICV) percent differences greater than acceptance criteria.

4.3.3.3 Glycols

The ethylene glycol and propylene glycol results for four samples were qualified as estimated (UJ) due to CCVs outside of project criteria (**Table 17**). Results for two samples for diethylene glycol and triethylene glycol were qualified as estimated (UJ) because of uncertainties related to manual calibration of a standard concentration.

4.3.3.4 Volatile Organic Acids

The samples collected in June 2014 and the sample collected from PGDW30 in August 2014 arrived at the subcontract laboratory outside of project pH requirements; results were qualified as estimated (UJ) (**Table 18**). Additional acetic acid, butyric acid, lactic acid, and pyruvic acid results were qualified as estimate (UJ) due to low LCS or MS/MSD recoveries.

4.3.3.5 Semivolatile Organic Compounds by Gas Chromatography/ Mass Spectrometry and Acrylamide

The sample obtained from PGDW41B in June 2014 was analyzed outside of the gas chromatography/mass spectrometry (GC/MS) tuning window, and the associated results were qualified as estimated (J or UJ) (**Tables 19A** and **19B**). A subset of the results for the sample collected from PGDW05 in June 2014 was qualified as estimated (UJ) due to a low surrogate spike recovery. The remaining qualifiers (UJ, three samples: 1,4 dichlorobenzene, 2 chlorophenol, and phenol) were assigned due to LCS percent recoveries that were less than acceptance criteria.

4.3.3.6 Pesticides

Reported concentrations of nitrogen and phosphorus-containing pesticides were less than the respective MDLs (**Table 20**). Results were acceptable for use with the qualification that the detection limit is estimated (UJ) due to ICV recoveries less than project criteria, analytes co-eluding through the columns, or analysis of sample extracts by the subcontract laboratory past the storage time for extracts specified in the lab QAPP. (Samples were extracted within the specified holding time after receipt.)

Of the organochlorine pesticide analyses, the CCV for the sample obtained from PGDW33 in June 2014 was analyzed outside of the Method 8081A time requirements; the associated results were qualified as estimated (UJ or J+) (**Table 21**). The remaining organochlorine pesticide qualifiers (UJ or J+) were assigned due to confirmation columns, ICVs or CCVs falling outside of project criteria.

Of the organophosphorus pesticide analyses, results for the sample collected from PGDW20 in August 2014 were qualified as estimated (UJ) due to a surrogate spike recovery less than project criteria (**Table 22**). The remaining qualifiers (UJ) were assigned due to ICVs or CCVs outside of acceptance criteria and analytes co-eluding through the columns.

4.3.4 Dissolved Gases

One of four coolers holding a portion of the samples collected from LD02 and PGDW20 on August 21, 2014 (SDG 260131) was delayed in shipping and arrived at the laboratory outside of temperature criteria. The associated results for method RSK-175 were qualified as estimated (UJ or J-) (**Table 23A**). Methane results for 20 samples were qualified as not detected (U) due to reported concentrations of methane in the associated method blank or trip blank samples. Field duplicate samples and Level IV analyses for Method RSK-175 were within project acceptance criteria.

Results for dissolved gases analyzed by GC-NOS were qualified as UP or JP (U/PM and J/PM in the data validation reports) due to the analyses not performed within 14 days of collection (**Table 23A**). However, the SAP specifies a holding time of 14 days for samples for dissolved gases by method RSK-175 whereas the holding time for GC-NOS is not specified; also, the methods use different sample containers. Therefore, the impact of performing the analysis after 14 days is not known.

Results analyzed by method GC-NOS were qualified as estimated, project management decision on use of data (JP, or J/PM in the data validation report); or, compound not detected, project management decision on use of data (UP, or U/PM in the data validation reports). The results analyzed by method GC-NOS were qualified because the data validation reviewer was able to perform a partial reconstruction of the results based on the data supplied by the laboratory. The duplicate analyses, computational checks, and other laboratory quality control provided a level of confidence in the data.

4.3.5 Radiochemistry

Radon-222 were acceptable for use, with results for 15 samples qualified as estimated (J or UJ) due to being analyzed by the subcontract lab outside of the project hold time of four days (**Table 25**). Other radon-222 and gross alpha results were qualified as estimated (J or UJ) because the associated MS/MSDs were outside of project criteria. Four results for gross alpha were rejected (R) due to field duplicate relative percent differences (RPDs) outside of project criteria.

Gross alpha results were qualified JP or UP (J/PM or U/PM in the data validation reports), because the WY Class I Domestic standard is "gross alpha particle radioactivity (including radium-226 but excluding radon and uranium)," whereas the EPA MCL and standard analytical methods apply to gross alpha radioactivity without qualifications. The analytical laboratory results were provided as gross alpha, whereas gross alpha activity excluding radon and uranium was listed in the SAP. (Note: Radon is not retained by the analytical method used because it is a gas and is released from the sample during processing). On **Table 25**, gross alpha results are compared to the EPA MCL, and calculated gross alpha results excluding uranium are compared to the WY Class I Domestic standard.

Strontium-90 results were qualified as UP (U/PM in the data validation reports) because the analytical method employed by the laboratory did not differentiate strontium-90 from other radioactive isotopes of strontium or the carrier used for the analysis. Nonetheless, the reported

activity in all samples was less than the MDL. Thus, the activity of all strontium isotopes was less than the MDL, and the activity of strontium-90 in particular was lower still.

4.3.6 Microorganisms

The results and data qualifiers for microorganism analyses are included in **Table 26A**. The laboratory duplicates for two total coliform results, ten iron-related bacteria results, and eight sulfate-reducing bacteria results were outside of project criteria and qualified as estimated (J or UJ). The field duplicate samples for two total coliform results, four iron-related bacteria results, and two sulfate-reducing bacteria results were qualified as estimated (J or UJ) due to field duplicate RPDs outside of project criteria.

4.3.7 Stable Isotopes

The stable isotope analyses results and data qualifiers are included in **Table 27**. Not all of the field duplicate pairs produced results for all isotopes, but the detected results were within project criteria. Veridian was unable to complete a full Level III or Level IV review of the stable isotope data because Isotech did not provide adequate information about the minimum required masses to generate results for several isotopes. Veridian also was unable to reconstruct the standards well enough to compare to the sample calculations that were provided, and the remaining calculations could not be verified because they are maintained within laboratory software. Stable isotope analyses have been qualified with J/PM (JP) or U/PM (UP) due to the partial review.

4.4 Results from Prior Sampling Events, Review of Data Quality and Report Completeness

4.4.1 Historical Groundwater Sampling Data, 1979-2008

Analytical data for groundwater sampling events prior to 2008 are included for LD02, PGDW05, PGDW20, PGDW23, PGDW30, PGDW41B, and PGDW44. The groundwater data were obtained from laboratory analytical reports except for the sample collected from PGDW05 on June 22, 2005 (WDEQ, 2015 summary table, analysis attributed to Energy Laboratories) and the samples collected from PGDW30 on December 7, 2007 (WDEQ, 2015, letter from Encana to well owner, analysis attributed to Energy Laboratories). Except for the October 2008 sample collected from PGDW05, no third-party data validation was available for review.

During each sampling event, an individual water-supply well or small group of study wells were selected for sampling. Additionally, the laboratories, methodologies, and MDLs were not uniformly selected across events. Earlier sampling tended to focus on general water-quality indicators while more recent sampling events included more analyses. Data from sources that were filtered or treated were not included in **Tables 12B, 13B, 14B, 24B** and **26B**.

The analytes listed below were only included in the analyses suite for one sample event:

- Aluminum, October 2008 (**Table 14B**)
- Antimony, September 2004 (**Table 14B**)

- Bromide, October 2008 (**Table 12B**)
- Cobalt, October 2008 (**Table 14B**)
- Cyanide, September 2004 (**Table 13B**)
- E.coli, April 2005 (**Table 26B**)
- Heterotrophic bacteria, April 2005 (**Table 26B**)
- Molybdenum, October 2008 (**Table 14B**)
- o-Phosphate, October 2008 (**Table 12B**)
- Slime-forming bacteria, October 2008 (**Table 26B**)
- Thallium, September 2004 (**Table 14B**)
- Total extractable hydrocarbons, November 2007 (**Table 24B**)
- Total Kjeldahl nitrogen, November 2011 (**Table 13B**)
- Total purgeable hydrocarbons, November 2007 (**Table 24B**)

4.4.2 US EPA Phase I to IV Groundwater Sampling, 2009-2011

In the US EPA Phase I-IV Pavillion reports, summary tables of analytical data do not include all of the results. Detections of organic compounds are summarized in the Phase I and Phase II reports, for samples collected in March 2009 and January 2010, respectively, and are provided in **Table 24C**.

As noted above, the dates of sampling of water-supply wells for each US EPA project phase are as follows:

- Phase I: March 2009
- Phase II: January 2010
- Phase III: October 2010
- Phase IV: April 2011

Table 1 in the Phase III-IV report (US EPA, 2011) summarizes the analyses performed on each sample. Based on this summary table, the following results are not provided in summary tables within the US EPA Phase I-IV reports:

- Iron, manganese, and nitrite results not presented in Table 2 of the Phase III-IV report (US EPA, 2011).

- Cyanide results not presented in Phase I (US EPA, 2009) or Phase III-IV reports (US EPA, 2011).

- Metals results not presented in Phase III-IV report (US EPA, 2011).

- Alcohols and VOCs (**Table 24C**) results not presented in Phase III-IV report (US EPA, 2011).

- Low molecular weight acids and glycols (**Table 24C**) not presented in Phase III-IV report (US EPA, 2011).
- SVOCs and PCBs (**Table 24C**) results not presented in Phase III-IV report (US EPA, 2011).
- Specific sample dates not listed for two wells sampled during Phase I and one well sampled during Phase II in Table 4a of Phase III-IV report (US EPA, 2011).
- Minimal data on TICs are provided in the Phase I and Phase II reports. No TIC results were summarized in the Phase II report (US EPA, 2010) and TICs were only reported qualitatively in the Phase I report (US EPA, 2009).

Groundwater sample results for the analytes and TICs listed above are available on the US EPA project website as raw analytical laboratory reports.

5. EVALUATION AND DISCUSSION

5.1 Gas Well Integrity

Gas well integrity, in a strict sense, refers to the soundness of the wellbore (casing, tubing, packer, annular spaces, cement behind casing, and wellhead seals). A breach in wellbore integrity may allow the movement of gas or other fluids (formation and/or fracture fluids) along the wellbore. In a broad sense, the upward seepage/migration of gas or other fluids from the production zone (through fractures or permeable pathways), as well as along an offset or abandoned well intersecting the production zone (interaction of gas wells), are often included in the assessment of well integrity. The following provides a brief discussion of these issues based on the Well Integrity Review Report (WOGCC, 2014) and the MBDCI evaluation of the Well Integrity Review Report (**Appendix G**).

5.1.1 Potential for Movement of Gas or Other Fluids from Hydraulically-Fractured Production Intervals

Within the Pavillion Gas Field, vertical or lateral seepage of gas or other fluids from the producing horizons where the hydraulic fracturing has taken place is extremely unlikely. First, these producing horizons become pressure sinks (where pressure is low) as gas is withdrawn during production. Fluids, especially gas, cannot flow away from this zone because the fluids will encounter higher pressures moving outward. Second, the small hydraulic fracturing fluid volumes employed in the Pavillion Gas Field make it unlikely for the fracture fluids to propagate a significant vertical distance. The typical treatment volumes reported for stimulating the occasional thin upper production zones between 1,400 and 2,000 ft bgs tend to be as small as 75 to 100 barrels of water. Calculations provided in the MBDCI evaluation (**Appendix G)** show that the fracture created in the impermeable rock by a 100-barrel stimulation may rise to a maximum of 30 ft above the top of the stimulation interval, assuming that all of the fluid remains in the fracture. When the stimulation volume doubles, with all other conditions unchanged, the fracture rise only increases by 26 percent. For example, in the Pavillion Gas Field, for a 1,000-barrel stimulation (including the volume of liquid CO_2), the fracture rise may be a maximum of 65 ft. The 30 to 65 ft estimated height of fracture rise is much smaller than the several hundred feet separating the highest production interval from the shallow permeable zones that intersect the water-supply wells included in the 2014 Groundwater Investigation.

5.1.2 Potential for Interaction with Adjacent Wellbores

There is no report of any interaction with active adjacent wellbores in the Pavillion Gas Field, which presumably would have been noted by changes in behavior in adjacent gas wells, increased gas or liquid production, or other effects. There have also been wells stimulated in proximity to previous wells that had been plugged:

- Pavillion Fee 34-03 and 34-03R, separated from W.E. Lloyd by 62 and 129 ft, respectively (**Figure 12E**). W.E. Lloyd 1 was plugged before the other two wells were drilled.

- Pavillion Fee 14-03 and 14-03W, separated from Mae H. Rhodes 1 by 274 and 345 ft, respectively (**Figure 12H**). Mae H. Rhodes 1 was plugged shortly after it was drilled in the 1950s, more than 20 years before the other wells were drilled.

- Tribal Pavillion 33-10B, separated from Govt Tribal 33X-10 by 360 ft (**Figure 12C** and **12D**). Govt Tribal 33X-10 was plugged approximately 10 years before Tribal Pavillion 33-10B was drilled.

Even for these cases, the small stimulation volumes noted above make it unlikely that the stimulated fractures could extend horizontally to the plugged offset wellbore and for gas or liquid from the stimulated interval to move upward along the plugged offset wellbore, the plugged offset wellbore would have to have integrity issues.

5.1.3 Potential for Seepage along the Wellbore

Seepage along the wellbore is the most probable pathway for gas or other fluids to reach shallow depths or even the surface in the Pavillion Gas Field. In this scenario, gas or other fluids from production zones or intermediate zones may move upward through channels in the production or surface casing cement, or through the open annulus behind the production casing if the top of the cement is below the surface casing shoe, or through both (**Figure 1, Appendix G**). This may arise if the production casing cement was not brought up to the surface casing shoe, poor quality hole cleaning before cementing leading to the development of a continuous void that can become a gas-filled vertical channel, or autogenous cement shrinkage after initial set leading to the development of a micro-annular space or channel for formation of a gas column. These potential pathways are considered in greater detail in the MBDCI evaluation of the Well Integrity Review Report (**Appendix G**).

Breaches in production casing, tubing, packers, or wellhead seals also may cause seepage along the wellbore, but these are less likely to occur and relatively easy to identify. Mechanical integrity tests were performed on five gas wells in the Study Area (Blankenship 4-8, Tribal Pavillion 23-10, Pavillion Fee 31-10, Pavillion Fee 41-10B, and Pavillion Fee 12-11W) and all wells were tested satisfactory (WOGCC, 2014). The WOGCC suggests that within the Study Area production casings are generally sound.

5.1.4 Potential Vertical Movement of Groundwater and/or Gas in Production Well Boreholes

Seepage along the wellbore has the potential to cause communication (gas and/or water) between shallow permeable zones (where the water-supply wells are completed) and intermediate zones (beneath the shallow permeable zones and above the gas production intervals) that are both penetrated by gas wells. **Figure 14** uses the water-supply well depths and the shallowest perforations of gas wells to illustrate the depth ranges of the shallow permeable zones and intermediate zones in the Study Area. For the analysis of potential communication, however, the shallow permeable zones and intermediate zones need to be determined on a well-by-well basis as they vary significantly from location to location.

When there is an intermediate zone pressurized with gas, the higher pressure or hydraulic head may cause or allow flow of gas and/or liquids (liquids include water and/or liquid hydrocarbons) upward into the shallow permeable zones with a lower entry pressure or hydraulic head. The likelihood of such communication is greater for gas wells with a sustained pressure in the annular space between the surface casing and the production casing (i.e., Bradenhead space), and is highest for gas wells where the top of production casing cement is below the surface casing shoe, thereby leaving an open section between the production casing and the borehole wall (**Figure 6, Appendix G**). When an open section is present, a free gas column will likely develop and exert pressure higher than the formation hydrostatic pressure near the top of the open section. This pressure difference may be sufficient to overcome formation entry pressure, allowing the entry of gas and/or liquids into the shallow permeable zones. As the water quality in the intermediate zones would be expected to be different than in the shallow permeable zones, including higher dissolved solids concentrations, such communication would introduce fluids of poorer quality into the shallow permeable zones.

Gas wells that are within 1,420 ft of the water-supply wells with an open section between the top of production casing cement and surface casing shoe can be readily identified in the cross sectional plots in the **Figure 12** series. For example in **Figure 12E**, gas well Pavillion Fee 31-10 has an approximately 1,500-foot section of production casing without cement below the surface casing shoe. Gas and/or liquids from intermediate zones, if present under pressure in this open section, may have a higher likelihood of seeping into shallow permeable zones than the surrounding gas wells with no open sections.

The presence of sustained Bradenhead pressure, proof that the Bradenhead space is not completely sealed, is often an indication of gas (and sometimes liquid) seepage along the wellbore. In the Bradenhead testing conducted by Encana in 2011 through 2013 (WOGCC, 2014), 11 wells (out of 41 tested) were observed to have pressure that, when bled off, recovered to measurable levels. Most of these wells were completed after 2000 and six showed production casing cement above the surface casing shoe. This indicates that older wells (pre-2000) do not necessarily present a greater risk of gas seepage than younger wells (post-2000), and that wells with production casing cement above the surface casing shoe are not necessarily less susceptible to gas and/or liquid seepage.

Analyses of tubing and Bradenhead gas samples from 10 of these 11 wells indicate that the Bradenhead gas is thermogenic, quite consistent in composition between wells, and not greatly different from the tubing gas from production zones. Pressure measurements show that 10 of the 11 wells have Bradenhead equilibration pressure higher than the pressure in production casing and tubing, and that eight wells tend toward a relatively high stable shut-in pressure of around 150-185 pounds per square inch (psi). These analyses and observations suggest that Bradenhead gas from these wells is most likely sourced from an intermediate zone (i.e. below the surface casing shoe) that contains non-commercial quantities of gas in one or more permeable groundwater zones.

The potential for communication between this intermediate zone and shallow permeable zones (if present and penetrated by the gas well) may be illustrated by the Bradenhead testing at gas wells Unit 44-10 and Pavillion Fee 12-11W:

- Gas well Unit 44-10 has surface casing set to 591 ft bgs and the top of production casing cement reportedly at 1,918 ft bgs. Bradenhead pressure was 150 psi initially and recovered to 105 psi after seven days of shut-in following a 15-day flow test. During the flow test, the Bradenhead flowed gas and water, with 410 barrels of water recovered in the first eight hours.

- Gas well Pavillion Fee 12-11W has surface casing set to 418 ft bgs and the top of production casing cement reportedly to the surface. Bradenhead pressure was 150 psi initially and recovered to 142 psi after seven days of shut-in following a 15-day flow test. During the flow test, the Bradenhead flowed gas and water with 4,303 barrels of water recovered.

In the examples above, the significant flow of water is proof that the actual pressure or hydraulic head at this intermediate zone is sufficiently high to overcome the hydrostatic pressure behind the production casing. In the first example, the open annular space above 1,918 ft bgs between the production casing top of cement and surface casing shoe, facilitates the upward seepage of gas and water. In the second example, the seepage of gas and water to the surface indicates the presence of channels in the production casing cement, because the production casing cement is reportedly to the surface. If a shallow permeable zone is present and penetrated by the wellbore, the high-pressure flow (gas and/or water) may very likely enter it.

While sustained Bradenhead pressure is often an indication of gas seepage, the absence of Bradenhead gas or sustained pressure, on the contrary, is not proof that there is no gas seepage along the wellbore, because rising gas may follow other pathways outside the surface casing when the cement seal within the Bradenhead annular space is competent.

Another indication of gas seepage along the wellbore is gas bubbling up around the wellhead when there is standing water at the surface or when the surface is wet after a rain event. Another indicator is vegetative stress (**Figure 2, Appendix G**). In this scenario, gas has migrated through channels in the surface casing cement or laterally into the adjacent formation and then upward. When this occurs, the soil gas tends to dissipate away from the wellhead. Gas bubbles were reported by the land owner near abandoned gas well Govt Tribal 33X-10 when standing water was present (**Table 9**). Other than that, there is no known record of monitoring and analyses for soil gas at the Pavillion Gas Field to assess whether seepage occurs elsewhere.

The sustained Bradenhead pressure and reported gas bubbling at the wellhead suggest that some gas wells in the Pavillion Gas Field are experiencing slow gas seepage. However, these are not direct evidence that gas (and sometimes water) seeping along the wellbore has entered or is entering shallow permeable zones in which the water-supply wells are completed. This would be very difficult to assess, because the entire process occurs in the subsurface. Collecting direct evidence from the surface requires having water supply or monitoring wells that intercept these

shallow permeable zones near the gas well. Furthermore, the water supply or monitoring wells would have to be constructed and sampled in advance of or in the very early phases of gas well development in order to demonstrate unequivocally that the presence of methane or changes in water quality in the water-supply or monitoring wells is associated with gas well development. Existing data from the Pavillion Gas Field is insufficient to demonstrate whether this has occurred or is occurring, and the analysis is confounded by the presence of naturally occurring gas in shallow permeable zones as described earlier.

5.1.5 Summary

In summary, seepage of gas or other fluids from production zones directly or along offset or abandoned gas wells is unlikely in the Pavillion Gas Field. The sustained Bradenhead pressure and anecdotal reports of gas bubbling at the wellhead suggest that some gas wells in the Pavillion Gas Field are experiencing slow gas seepage within the annular space between the production casing and the well bore. It is not known however, if gas (and sometimes liquid) seeping along the gas wells has entered or is entering shallow permeable zones in which the water-supply wells are completed. Even if such occurrences can be demonstrated, the relative contribution of gas seepage along gas wells versus natural upward migration of gas would be very difficult to quantify.

5.2 Gas Well Pits as Potential Source of Water-Quality Impacts

Gas well pits, especially older pits constructed prior to 1984, are potential sources of impacts to groundwater quality in the Pavillion Gas Field. The older pits are commonly unlined and may have contained invert mud (i.e., oil-based mud) or other petroleum product from drilling or exploration. Most of the older pits are invert mud-type reserve/production pits, and are of particular concern because of the characteristics of the waste materials and the reported impacts to shallow groundwater at some of these pits. The LSND mud-type and the KCl polymer-type cuttings pits, constructed under more rigorous regulations, may also be potential, although less likely, sources of groundwater quality impacts. The WOGCC's Pit Review Report (WOGCC, 2015) provides a detailed discussion of the use, status, closure, and reclamation information of the pits, as well as their potential to contribute to water-quality issues at the water-supply wells. A summary of the history of pits and those within 1,420 ft of the water-supply wells included in the 2014 Groundwater Investigation is provided in Section 2.5.

The WOGCC has primary regulatory authority over gas well pits and waste materials contained in the pits. If oil-contaminated soils are present in a pit or its immediate area, the WOGCC's risk-based closure method - the Oil Contaminated Soil Remediation Ranking System (OCSRRS) is typically applied. The OCSRRS scores the pit based on sensitivity of the site to contaminant migration and assigns a corresponding total petroleum hydrocarbon (TPH) clean-up level in soils that must be met. Other rigorous detailed site and health/environmental assessment is also suggested. It is important to note that the OCSRRS process is for oil-contaminated soils only and does not address inorganic constituents.

If a pit is the source of groundwater quality impacts, WDEQ regulations are primary, and the WDEQ VRP provides specific individual constituent concentration limits that must be met, including soil concentration limits that are considered protective against contaminant migration to groundwater.

According to the WOGCC (2015), investigations were conducted at 31 of the 49 invert mud-type pits. Twenty-six were accepted in the WDEQ VRP in September 2005. Encana subsequently requested, and was granted, approval to withdraw VRP applications for 23 pits due to site access problems or because investigations were to be conducted under the WOGCC direction. Five sites were reinstated into the VRP resulting in a total of eight sites enrolled as of November 2014. Subsequently, four of the pits in the VRP were remediated and granted Certificates of Completion (COC) in April and June 2015 leaving 4 pits remaining in the VRP. Only two of those closed pits, Blankenship 4-8 (COC April 30, 2015) and Tribal 14-2 (COC April 29, 2015) are located in the Study Area. Other types of pits are either not investigated or not enrolled into the VRP. The WOGCC's Pit Review Report, however, does not provide any data evaluation or in-depth analyses for the pits enrolled in the VRP regarding their potential impact to water-supply wells. **Table 5** and **Figure 13** provide a summary of the investigation status for the pits within 1,420 ft of the water-supply wells included in the 2014 Groundwater Investigation.

Pits enrolled in the VRP by definition, are at sites where groundwater quality has been degraded. Groundwater contamination near a pit location, however, does not necessarily result in impacts to nearby water-supply wells; as that outcome would depend on many factors, such as source mass, pathway, hydraulic gradient (observed groundwater elevations indicate downward flow within the Study Area), transport characteristics (e.g., dispersion and retardation), and the water-supply well's zone of capture. For example, limited contaminant mass emanating from a pit could be attenuated by dilution, adsorption, and biodegradation along the path before reaching a water-supply well. If a pit is hydraulically downgradient and not within the capture zone of a water-supply well, the well would not be impacted; and if a water-supply well is screened in a zone shallower or deeper than the zone of contamination, it may not be impacted if these zones are hydraulically isolated. On the other hand, attributing water quality issues in a water-supply well to a nearby pit with known groundwater quality degradation could be challenging, as this may require obtaining baseline data prior to significant changes in water quality, establishing a clear pathway using data from a well-designed monitoring program (i.e., number of wells, locations, depths, and frequency), and ruling out other potential sources of impacts (e.g., naturally occurring or from anthropogenic sources).

A pit without known groundwater contamination is no guarantee that it has not or will not cause groundwater contamination to a nearby water-supply well. Local hydrologic and hydraulic conditions may vary seasonally, with potential significant changes over the pit's lifetime, and thus a limited investigation conducted at a certain point in time is not likely to be fully representative. Examples include the absence of groundwater near the bottom of a pit during investigation (groundwater could occur at the bottom of the pit at certain times), the absence of targeted contaminants in groundwater from limited samples (these samples could have missed the area/zone of groundwater contamination), and the failure to sample and analyze other

potential contaminants (petroleum hydrocarbons are usually the targets but other water quality parameters are often not assessed).

Investigation, monitoring, and remediation at the pit locations are often limited to the zone of shallowest groundwater, reflecting the judgment that the relatively deep sandstone lenses in which most water-supply wells are completed are likely not in hydraulic connection with the shallow alluvial/colluvial or Wind River deposits in which the pits are located. While this may be true considering the generalized nature of the sandstone lenses (thin, lenticular, and hydraulically isolated to varying degrees), site-specific conditions may vary significantly. For example, some of the water-supply wells may be completed in the shallow deposits in which the pits are located; the siltstones and claystones in between the sandstone lenses are not totally impermeable, albeit significantly less permeable than the sandstones; there may be fractures in the less permeable materials that act to bridge the sandstone lenses; and some of the sandstone lenses exposed at surface may extend to a large depth. In particular, groundwater has been shown in past Wind River aquifer studies to move through the less permeable materials (USGS, 1959; USGS, 1969). Specifically, in a pump test conducted for the Riverton public water-supply wells completed in the Wind River Formation, drawdown was observed in 10 monitoring wells at depths from 145 to 662 ft and at distances up to 1 mile (USGS, 1959). Overall, as pointed out by the WOGCC (2015), existing data is insufficient to characterize groundwater flow patterns and gradients and to assess the degree of hydraulic connection between the surficial deposits and the Wind River aquifers in the vicinity of the water-supply wells.

Based on the results of the 2014 sampling, there is a potential for inorganic compounds (e.g., chloride, potassium, sulfate) from gas pits to be contributing to the high levels of salts and other compounds reported in the water-supply wells. Further analysis is needed to assess whether investigations and/or remediation at pit locations was sufficient to protect groundwater quality at the water-supply wells. Once all of the pits entered into the VRP and those pits recommended for investigation by the WOGCC Pit Report have been characterized, a full review of available data for pits under the VRP and WOGCC is needed and can be augmented with information from studies in other areas or published guidance. It is also suggested that a comprehensive conceptual site model for contaminant migration from pits be developed to guide further investigation and analysis. More discussion of related issues and suggestions are available in the review summary of the Pit Review Report (**Appendix I**).

5.3 Source of Methane in Water-Supply Wells

5.3.1 General Isotopic and Chemical Signatures of Methane Gas

Analyses of isotope ratios (δ13C for carbon-13 and δD for deuterium (hydrogen-2)) and gas compositional data (relative abundance of methane [C1], ethane [C2], and propane [C3], etc.) can be insightful in understanding the source and alterations of methane in samples from the water-supply wells. These analyses can help assess whether the methane is thermogenic, biogenetic, or a mixture of both, if the methane has undergone biodegradation, and if changes in gas composition have occurred during migration. It is important to note that in the June and

August 2014 groundwater samples, reported methane concentrations (maximum 1,300 µg/L) were less than the WOGCC notification level for water sources of 10,000 µg/L.

Natural gas can be of either biogenic or thermogenic origin. Biogenic gas is generated by the breakdown of organic matter by bacteria at low temperatures using carbon dioxide reduction or fermentation. Biogenic gas consists almost exclusively of methane, carbon dioxide, and hydrogen sulfide, having C1/(C2+C3) ratios greater than 1,000, carbon isotope ratios of methane ($\delta 13C\text{-}CH_4$) ranging from -110‰ to -50‰, and deuterium isotope ratios of methane ($\delta D\text{-}CH_4$) ranging from -400‰ to -150‰ (Bernard et al., 1977; Whiticar, 1999). Thermogenic gas, including petroleum-related hydrocarbon gases, is generated at higher temperatures by thermal cracking and degradation processes of more deeply-buried organic matter. Thermogenic gases generally have C1/(C2+C3) ratios smaller than 50, $\delta 13C\text{-}CH_4$ values ranging from -50‰ to -20‰, and $\delta D\text{-}CH_4$ values ranging from -275‰ to -100‰ (Bernard et al., 1977; Whiticar, 1999).

Mixing, migration, and biodegradation (aerobic or anaerobic oxidation) can alter the isotopic signatures of methane and the composition of gas (Bernard et al., 1977; Whiticar, 1999). A mixture of biogenic and thermogenic gas will exhibit isotope ratios and gas composition somewhere in between the regions characteristic of each type of gas. Migration of gas in the subsurface (e.g., advection, dispersion, diffusion) may result in the relative abundance or loss of certain gases, with little change in the isotope ratios of methane. For example, the upward migration of thermogenic gas may result in the preferential loss of C2 and C3 (e.g., higher solubility) relative to methane and thus an increase in the C1/(C2+C3) ratio. Biodegradation of natural gas tends to result in the enrichment of the isotopes (i.e., increase in isotope ratios) and the relative loss (i.e., a decrease in C1/(C2+C3) ratio) of methane, as methane is relatively more biodegradable.

Isotope ratios of methane and gas compositional data are often used in combination to identify the source and alterations of natural gas. The CD diagram (i.e., $\delta D\text{-}CH_4$ versus $\delta 13C\text{-}CH_4$) and the Bernard diagram (i.e., C1/(C2+C3) ratios versus $\delta 13C\text{-}CH_4$) are among the often used for this purpose.

The isotopic signature of methane and gas composition in samples from the water-supply wells, the presence of gas in shallow groundwater in the Pavillion Gas Field, and the construction of gas wells surrounding the water-supply wells are discussed below to evaluate the potential source(s) of methane in water-supply wells.

5.3.2 Isotopic Signature of Methane and Gas Composition in Water-Supply Wells

Gas in samples obtained from water-supply wells is thermogenic gas that shows signs of alteration by biodegradation and migration. Gas compositional and isotopic data do not suggest a shallow biogenic source.

Analyses of δ13C and δD in dissolved methane samples from the water-supply wells were compared with analyses of δ13C and δD in methane from produced gas samples (i.e., gas obtained from producing wells). Data for dissolved methane in water samples are available from the June and August 2014 sampling and the US EPA Phases II, Phase III, and IV sampling. Data

for produced gas samples from both the Wind River Formation and Fort Union Formation are available from the US EPA Phase II and from Johnson and Rice, 1993. A comparison was also made between δ13C-CH_4 and the gas composition. The compiled data are available in **Appendix P**.

Based on analyses of carbon-13 and deuterium isotope abundance, methane in the samples from the water-supply wells is thermogenic in origin, showing signs of alteration by biodegradation (**Figure 15**). The isotope ratios for the produced gas samples are very similar, with gas sourced from the Fort Union Formation being indistinguishable from gas sourced from the Wind River Formation. The two clusters of data for gas samples from the US EPA appear to be duplicate samples analyzed by two separate laboratories. These analyses show a bias between laboratories of approximately 10‰; nevertheless, they are within the region of thermogenic gas. The samples from the water-supply wells either fall within the region of thermogenic gas, or are enriched in carbon-13 and/or deuterium (i.e., three PGDW23 samples, one PGDW30 sample, PGDW41, and PGDW44). Enrichment of these heavier isotopes is attributable to biodegradation of thermogenic methane. The US EPA had a similar finding in their isotopic analysis of methane from water-supply wells (US EPA, 2011).

Comparison of carbon-13 abundance with C1/(C2+C3) ratios suggests that methane in the samples from the water-supply wells is thermogenic in origin, showing signs of alteration by migration and biodegradation (**Figure 16**). All of the produced gas samples fall closely within the region of thermogenic gas, indicating that gas sourced from the Fort Union Formation is indistinguishable from gas sourced from the Wind River Formation. Samples from PGDW20 also fall within the region of thermogenic gas, indicating little alteration by migration and biodegradation. Samples from PGDW30 are depleted in ethane and propane versus methane, indicating significant alteration by migration. Samples from PGDW23 are enriched in carbon-13 while depleted in ethane and propane versus methane, indicating significant alteration by both biodegradation and migration. The US EPA had a similar finding in its analysis of gas composition and methane isotopes from water-supply wells (US EPA, 2011).

5.3.3 Potential Sources of Methane in Water-Supply Wells

There are two potential sources of methane in water-supply wells: 1) naturally occurring methane and 2) methane as a result of oil and gas exploration/production. Methane in water-supply wells could be from either source or a mixture of both sources, and is thermogenic in origin as described above.

Naturally occurring methane or gas in shallow permeable zones in which water-supply wells are completed is known to be present either before the initial exploration/production or before the extensive exploration/production of the Pavillion Gas Field. This condition is described in Section 2.6 and summarized in Section 5.1.

The presence of naturally occurring methane in shallow permeable zones within the Pavillion Gas Field is not unexpected due to the absence of a regional confining unit and the presence of commercial gas-producing reservoirs as shallow as 1,500 ft bgs. The similarity in isotopic

characteristics between the Fort Union Formation and the much shallower Upper Wind River Formation is evidence that there are natural pathways whereby the deeper thermogenic gases are gradually seeping to the surface. As gas migrates upward into shallow permeable zones, its compositional and isotopic characteristics may be altered, as illustrated in Section 5.6.2, and do not necessarily resemble the characteristics of the produced gas, which is a mixture of gas from multiple producing intervals.

Based on the above observations and analyses, it is almost certain that part of the methane observed in the water-supply wells included in the 2014 Groundwater Investigation is naturally occurring and not a result of oil and gas exploration and/or production.

Methane as a result of oil and gas exploration/production may enter shallow permeable zones in which the water-supply wells are completed through three potential pathways: 1) gas seepage along the wellbore, 2) gas seepage from production zones, and 3) gas migration along an offset or abandoned well intersecting production zones. As discussed in Section 5.4, the first pathway occurs as a result of wellbore integrity issues, the second pathway occurs from within the production horizon, and the third pathway is due to the interaction of gas wells. As discussed in Section 5.4, vertical or lateral gas seepage from the producing horizons where the hydraulic fracturing has taken place is extremely unlikely because these producing horizons become pressure sinks (where pressure is low) as they are depleted. Also, there is no report of any interaction with adjacent wellbores in the Pavillion Gas Field, and the small stimulation volumes typically employed in the Pavillion Gas Field make it highly unlikely that the stimulated volume could extend to the offset well, from which gas from the stimulated interval could move upward along the offset well.

Gas seepage along the wellbore as a result of wellbore integrity issues is potentially the most likely mechanism for gas to enter shallow permeable zones in the Pavillion Gas Field. Gas from production zones or intermediate zones could enter shallow permeable zones with a lower gas-entry pressure, through channels in the production or surface casing cement, through the open section of the production borehole where the top of production casing cement is below the surface casing shoe, or through both.

As discussed in Section 5.1, the sustained Bradenhead pressure from a number of gas wells and reported gas bubbling at the wellhead of one gas well suggest that some gas wells in the Pavillion Gas Field are experiencing slow gas seepage. However, these do not constitute direct evidence that gas seeping along the wellbore has entered or is entering the shallow permeable zones. Existing data from the Pavillion Gas Field is insufficient to demonstrate whether this has occurred or is occurring, confounded especially by the presence of naturally occurring gas in shallow groundwater.

5.3.4 Occurrence of Free Gas in Borings for Water-Supply Wells

One example of free gas in a water-supply well boring includes the gas encountered at 500 ft bgs in a water-supply well drilled in 1951 ("Camp 9" well). The well was subsequently plugged back

and completed at a shallower depth (300 ft); it was located immediately northeast of the Pavillion Gas Field and the Study Area (USBR, 1951).

Naturally-occurring gas is known to be present in the Pavillion Gas Field as shallow as 500 ft bgs. Blowout of the water-supply well intended to replace PGDW05 in December 2005 (see details in Section 2.5.3.3) is another example of free gas in a water-supply well boring. The replacement well was drilled to a depth of approximately 550 ft bgs, with a screen and gravel pack at 520 to 540 ft bgs. When developing the well using air lift, gas began flowing to the surface; the well was subsequently plugged.

In addition, gas wells Tribal Pavillion 11-11 (completed in 2011) and Tribal Pavillion 11-11B (completed in 2002), the third and fifth closest to the replacement well for PGDW05 (**Figure 12B**), have gas identified on logs at 566 and 568 ft bgs, respectively (WOGCC, 2007). Therefore, naturally occurring gas is very likely the source of gas in the water-bearing zone where this replacement well was screened.

It is not unreasonable to consider nearby gas wells for potential contributing factors. Gas wells Tribal Pavillion 24-02 (completed in 2004) and Tribal 14-2 (completed in 1981), the first and second closest to the replacement well (**Figure 12B**), have surface casing extending to 552 and 584 ft bgs, respectively, top of production casing cement at 558 and 2,200 ft bgs (primary cementing), respectively, and shallowest gas identified on logs at 928 and 674 ft bgs, respectively (WOGCC, 2007). Hypothetically, gas could migrate from these gas-charged zones upward along the wellbores (in particular, where the primary cementing did not bring cement to the surface casing shoe) and then into the water-bearing zone intercepted by the replacement well. Whether such a pathway exists, however, would be extremely difficult to confirm. Even if such a pathway is confirmed, it would be a challenge to assess whether its contribution to the blowout is significant relative to naturally occurring gas.

It is worth noting that within the Study Area there are a number of water-supply wells (including PGDW32 drilled in 1983) that were successfully completed at depths greater than 500 ft bgs without reports of gas (**Figures 8** and **9**). LD02, drilled in 1994, is also known to have an original total depth of 610 ft, although it was not used due to odor and poor water quality. These additional observations suggest that the permeable zones deeper than 500 ft bgs may or may not be gas charged, and are, in general, disconnected in terms of gas flow.

5.3.5 Summary

In summary, methane in water-supply wells included in the 2014 Groundwater Investigation is almost certain to contain naturally occurring methane. Gas seepage, most likely from an intermediate depth along the wellbore of gas wells, could have contributed and may still be contributing to the methane in water-supply wells. However, it is not known with certainty if this has occurred and to what extent this has occurred based on existing information. It is important to note that in the June and August 2014 groundwater samples, reported methane concentrations (maximum 1,300 µg/L) were less than the WOGCC notification level for water sources of 10,000 µg/L.

5.4 Chemical Characteristics of Local Groundwater

5.4.1 Similarities in Chemical Characteristics of Groundwater from Water-Supply Wells

The general chemical characteristics of the groundwater produced by the 14 water-supply wells included in the study are consistent with those reported for the Wind River aquifer across the Wind River Basin. The predominant cation and anion are sodium and sulfate (**Figure 17A**). Reported TDS concentrations in samples from the water-supply wells ranged from 560 to 6,350 mg/L (**Table 12A**). Water produced by each of the 14 water-supply wells is alkaline (i.e. pH greater than 7.00) (**Table 11**). Separate plots for June 2014 (**Figure 17B**) and August 2014 (**Figure 17C**) allow individual data points to be more readily discerned.

5.4.2 Groundwater Quality Variation

Groundwater from shallow well PGDW45 (total depth (TD) of 48 ft bgs) is an exception to the common sodium sulfate water; it is predominantly calcium bicarbonate. Also, the predominant cation in the groundwater from shallow well PGDW33 (TD 30 ft bgs) is calcium, and it has the second-highest proportion of bicarbonate (**Figure 17A**). The pH of groundwater from these two wells is also the lowest and is near neutral, at approximately 7.1 to 7.2 (PGDW33) and 7.0 to 7.2 (PGDW45). The groundwater quality in these two wells appears to be influenced by the infiltration of shallow groundwater. The TDS concentrations also exhibit apparent seasonal variations, with TDS concentrations declining in August near the end of the irrigation season (PGDW33, 1,350 and 1,180 mg/L in June and August, respectively; PGDW45 820 and 740 mg/L in June and August, respectively).

In the groundwater samples from PGDW41A, chloride constitutes approximately 20 to 25 percent of the anions, with the remainder primarily sulfate. Groundwater with the greatest TDS concentrations (from PGDW41A, PGDW41B, PGDW44, and PGDW49 with reported TDS concentrations greater than 4,000 mg/L) also contains a somewhat greater proportion of calcium, approximately 20 to 40 percent, rather than mostly sodium as in other deeper wells (**Figure 17A**).

Groundwater geochemical characteristics of the water-supply wells included in the study do not appear to correlate with depth. Plots of sulfate and TDS concentrations show scatter (**Figure 18**). As shown on the plots, TDS and sulfate concentrations are relatively low in groundwater from shallow wells PGDW33 and PGDW45, and from the deeper well PGDW32 (TD 675 ft bgs) in addition to wells with intermediate depths. This lack of apparent correlation is in contrast with general trends reported from regional studies, and suggests that the geochemical conditions of the specific permeable zone(s) intercepted by the water-supply wells are a more important factor than well depth.

5.4.3 Groundwater Quality Temporal Trends

Limited baseline water-quality data that predates development of the Pavillion Gas Field hinders reaching firm conclusions on causes and effects of reported water-quality changes over time. Previous USGS studies included sampling of water-supply wells between 1948 and 1996;

unfortunately, the descriptions of historical sample locations do not seem to correlate with water-supply wells included in this study. Therefore, there is limited knowledge of historical trends in groundwater quality that predates more intensive development of the Pavillion Gas Field around 1980 and later through the 2000s.

PGDW05 was sampled for major cations and anions in September 2004 in advance of the completion of the nearest gas well, Tribal Pavillion 24-02 in October 2004 and the subsequent completion of well Tribal Pavillion 21-11B; however, other gas wells within 1,420 ft of PGDW05 were completed in advance of this sampling event: Tribal 14-2, Pavillion Fee 11-11, and Pavillion Fee 11-11B (**Figure 12B**). Gorody (2008) provides a summary of the sampling results from 2004 and 2007. A series of Stiff diagrams depicting the concentration of major cations and ions for samples collected in September 2004, August 2007, October 2007, and November 2007 show no qualitative change in groundwater chemical composition, and a slight decline in overall concentration with time. The reported concentrations of major cations, major anions, and TDS in the 2004 and 2007 samples are consistent with results of additional sampling in 2008, with results of the US EPA sampling in 2009 to 2011 (**Table 12C**), and with results from the June and August 2014 sampling events (**Table 12A**).

PGDW20 was first sampled by the owner in 1988 after his purchase of the property in 1985. Reported concentrations of sodium, sulfate, and TDS in the sample were 170, 250, and 532 mg/L, respectively. The owner reported that the water quality declined rapidly in 1992, with a strong odor of rotten eggs and a bad taste. He also reported that on three occasions the water turned black for "a couple of weeks" and then slowly cleared (WDEQ, 2015). Following the decline in water quality, the well was sampled in May 1992. Reported concentrations of sodium, sulfate, and TDS increased to 1,100, 3,000, and 4,600 mg/L, respectively (**Figure 19**). Results from another sampling event in 1993 were similar. Reported results for a sample obtained in 1997 were anomalous, in that the reported sulfate concentration of 4,630 mg/L exceeded the reported TDS concentration of 3,950 mg/L. Relative to the sampling results from 1992 and 1993, concentrations of sodium, sulfate, and TDS declined somewhat by June and August 2014 to 520 to 600, 1,300, and approximately 2,000 mg/L, respectively.

The nearest gas wells to PGDW20, Unit 22-12, Pavillion Fee 13-12, and Pavillion Fee 23-12 were completed in January 1980, June 2001, and September 2001, respectively (**Figure 12A** and **Table 3**). Unit 22-12 was reworked in April 1993, with additional perforations made between 1,687 and 2,374 ft bgs with no treatment (WOGCC, 2014). A reserve production pit containing OBM was located adjacent to gas well Unit 22-12.

5.4.4 Groundwater Quality Spatial Trends

The sparse density of data points (14 water-supply wells spanning nine sections or square miles of land as shown in **Figure 13**) and the lenticular nature of the water-bearing zones prevent the use of iso-concentration maps to delineate the spatial distribution of groundwater quality parameters. These water-supply wells are likely completed in different water-bearing zones of different depths that are hydraulically disconnected. Without a spatial continuity in the water-

bearing zones, iso-concentration maps based on these data points using interpolation algorithms are simply not feasible. Such maps may be developed on a smaller scale with multiple data points from the same water-bearing zone, or on a larger scale in which the individual water-bearing zones can be conceptualized as one regional aquifer with the use of aggregate statistics. The existing data are insufficient to support either of the two situations.

The existing data are insufficient to determine if a spatial correlation exists between pits and pit-derived constituents in groundwater samples from nearby water-supply wells. This can be illustrated by the locations of KCl polymer-type pits relative to the major cations and anions in the water-supply wells (**Figures 20** and **21**). If the KCl polymer-type pits are a source of inorganic constituents in groundwater, one may expect higher concentrations of potassium and chloride in water-supply wells close to the pits and vice versa, neglecting other factors such as well depth, transport pathway, and natural variability of these constituents. **Figures 20** and **21**, however, do not show such a pattern. Specifically, water-supply wells that are within 1,420 ft of the KCl polymer-type pits (i.e., PGDW30, PGDW49, PGDW14, PGDW44, and PGDW23) show a large concentration variation in major cations and anions including potassium and chloride, similar to the other water-supply wells that are not within 1,420 ft of the KCl polymer-type pits. If factors such as well depth, transport pathway, and natural variability are considered, it will be more difficult to identify any spatial trends even if more data points are made available.

5.5 Exceedances of Water-Quality Standards and Comparison Values in Water-Supply Wells

5.5.1 Constituents Naturally Occurring in Pavillion Area Groundwater

Naturally occurring constituents include dissolved salts, metals, and radionuclides. Reported concentrations of sodium, sulfate, and TDS were greater than drinking water standards or comparison values in samples obtained from all of the 14 water-supply wells included in the study (sulfate in samples obtained from PGDW45 is the one partial exception).

Concentrations of aluminum, iron, manganese, lithium, thallium, and uranium were greater than drinking water standards or comparison values in a subset of the samples obtained from the water-supply wells, as were the reported activity of gross alpha and radon-222. Reported gross alpha activity was attributable to uranium. In samples from PGDW41A, reported concentrations of chloride and nitrate were greater than the respective drinking water standard or comparison value. The sum of total radium-226 plus radium-228 was greater than the WY Class I Domestic standard in the samples collected from PGDW41B.

The pH exceeded the WY Class I Domestic standard and the EPA SDWR in samples obtained from four of the water-supply wells. Standards for turbidity are related to water-supply treatment issues, and are not further considered.

5.5.1.1 Sodium

In all of the groundwater samples from the 14 water-supply wells, the reported concentration of sodium exceeded the EPA DWA of 20 mg/L (**Table 12A**).

The EPA DWA for sodium is intended to reduce the total daily sodium intake for individuals. Excessive sodium in the diet is associated with high blood pressure (ATSDR, 2010). The EPA DWA of 30 to 60 mg/L for individuals not on a sodium-restricted diet is based on the taste threshold.

5.5.1.2 Iron and Manganese

Reported concentrations of ferrous iron and iron (all forms) in samples from PGDW41B and PGDW44, and iron in the dissolved samples from LD02 and PGDW05 were greater than the WY Class I Domestic standards and the EPA SDWR (**Table 12A**).

The WY Class I Domestic standards and the EPA SDWR for iron and manganese are based on aesthetic effects. At sufficient dissolved concentrations, iron will form red oxyhydroxide precipitates that stain laundry and plumbing fixtures. Similarly, manganese will create black oxide stains (Hem, 1985).

5.5.1.3 Sulfate

Concentrations of sulfate in all of the groundwater samples collected from the 14 water-supply wells exceeded the WY Class I Domestic standard and the EPA SDWR, with some exceptions in samples collected from PGDW45. In a subset of the samples, the reported concentrations were greater than the EPA DWA of 500 mg/L (**Table 12A**).

The WY Class I Domestic standard and the EPA SDWR of 250 mg/L are equal to the taste threshold (US EPA, 2012). At higher concentrations, sulfate will have a laxative effect; the EPA DWA of 500 mg/L is intended to prevent acute onset diarrhea (ATSDR, 2010).

5.5.1.4 Total Dissolved Solids

Concentrations of TDS in all samples obtained from the 14 water-supply wells were greater than the WY Class I Domestic standard and the EPA SDWR of 500 mg/L (**Table 12A**).

WY Class I Domestic standard and the EPA SDWR of 500 mg/L is based on palatability. Water with a TDS concentration of 1,000 mg/L is considered slightly saline. Water with high TDS will also lead to mineral deposits and staining of fixtures and cookware (US EPA, 2013a).

5.5.1.5 Aluminum

Aluminum concentrations were greater than the EPA SDWR in total sample fractions collected in June 2014 from PGDW32 (duplicate sample) and PGDW44 (**Table 14A**).

WY Class I Domestic standard and the EPA SDWR of 50 mg/L for aluminum are based on aesthetic effects such as colored water (US EPA, 2013a).

5.5.1.6 Total Arsenic

Arsenic concentrations exceeded the EPA MCL in both total fraction samples but not the dissolved sample fraction samples from PGDW41A (June and August 2014) and PGDW49 (June 2014 sample). The reported concentrations of 13, 11, and 11 µg/L were marginally greater than the EPA MCL of 10 ug/L (**Table 14A**). Adsorption by or co-precipitation with ferric hydroxide may account for the lesser arsenic concentrations in the dissolved sample fractions (Hem, 1985).

Though a naturally occurring element, arsenic is known to cause gastrointestinal irritation and is classified by the US EPA as a known human carcinogen (i.e. Cancer Group A). At the concentrations reported in samples from water-supply wells included in the study, gastrointestinal irritation may occur, while the initial effects associated with cancer are observed at doses associated with greater concentrations in drinking water (ATSDR, 2010).

5.5.1.7 Lithium

Lithium concentrations were greater than the WY DWEL in the samples collected from PGDW41A, PGDW41B, PGDW44, and PGDW49 (**Table 14A**).

The WY DWEL of 66.7 µg/L is based on the non-carcinogenic toxicity from the US EPA Provisional Peer Reviewed Toxicity Values. This was based on the lower bound of the serum lithium concentration range for clinical data related to oral lithium therapy for treatment of bipolar affective disorders. Effects associated with lithium therapy include impaired renal concentrating ability, and neurological side effects, including lethargy, fatigue, weakness, tremor, and cognitive impairment (US EPA, 2008).

5.5.1.8 Thallium

Thallium concentrations exceeded the EPA MCL in some of the samples collected from PGDW14, PGDW41A, PGDW44, PGDW45, and PGDW49 (**Table 14A**).

The EPA MCL for thallium is intended to prevent chronic health effects, including hair loss, changes in blood, or problems with the kidneys, intestines, or liver (US EPA, 2013b).

5.5.1.9 Uranium and Gross Alpha Activity

Uranium concentrations exceeded the EPA MCL of 30 µg/L and the EPA DWEL of 20 µg/L in the samples collected from PGDW33, PGDW41A, PGDW45 and PGDW49, except that the August 2014 samples collected from PGDW45 were greater than the EPA DWEL but less than the EPA MCL (**Table 25**). Reported gross alpha activity exceeded the EPA MCL in the samples collected in June and August 2014 from PGDW14, PGDW33, and PGDW41A, and the sample collected in June 2014 from PGDW49. Gross alpha activity appears to be attributable primarily to uranium.

Uranium is classified by the US EPA as a known human carcinogen (i.e. Cancer Group A), due to its radioactivity as an alpha emitter. Consumption of uranium in drinking water may also result in chemical toxicity to the kidneys (US EPA, 2013b).

5.5.1.10 Radon-222

Reported radon activity exceeded the EPA MCL in the samples collected in June and August 2014 from PGDW14, PGDW32, PGDW41A, PGDW44, PGDW45, and PGDW49, and the sample collected in June 2014 from PGDW33 (**Table 25**).

Radon is classified by the US EPA as a known human carcinogen (i.e. Cancer Group A). Radon is a product of radioactive decay of naturally occurring uranium, and is present in the soil as a gas and in groundwater as a dissolved gas. Radon is radioactive due to it being an alpha particle emitter. Radon gas escapes from water when it is used for showering, washing dishes, and cooking. When inhaled, the alpha particle radiation damages lung tissue cells leading to lung cancer (US EPA, 2012b).

5.5.1.11 Naturally-Occurring Constituents Greater than Drinking Water Standard or Comparison Value in a Single Well

In both samples collected from PGDW41A in June and August 2014, concentrations of chloride exceeded the WY Class I Domestic standard and the EPA SDWR of 250 mg/L, and concentrations of nitrate exceeded the EPA MCL and WY Class I Domestic standard of 10 mg/L (**Table 12A**). In the samples collected from nearby PGDW41B, concentrations of both chloride and nitrate were less than the drinking water standards.

WY Class I Domestic standard and the EPA SDWR of 250 mg/L for chloride are based on taste; water with excessive chloride tastes salty.

The EPA MCL and WY Class I Domestic standard of 10 mg/L for nitrate is based on potential health effects on infants. Infants under six months who consume water with elevated nitrate concentrations may develop methemoglobinemia (blue baby syndrome) or shortness of breath (US EPA, 2013b).

In groundwater, concentrations of nitrate greater than approximately 1 to 2 mg/L are generally associated with animal manure, sewage or septic system effluent, nitrogen fertilizers, and municipal waste landfills (Chapelle, 2001). Potential nearby surface sources of nitrate near PGDW41A include the septic system to the southeast (septic tank approximately 130 feet from PGDW41A and PGDW41B), the horse and cow corral (approximately 100 feet away), and irrigated fields. As discussed in Section 5.7.1.5, stable isotope data for nitrogen and oxygen suggest that the potential source of nitrate may be human or animal waste that has undergone subsequent denitrification. However, the lower nitrate concentrations in samples from the shallower well (PGDW41B) are counter indicative.

The reported activity total radium-226 plus radium-228 in the samples from PGDW41B exceeded the WY Class I Domestic standard of 5 pCi/L.

Radium is classified by the US EPA as a known human carcinogen (i.e. Cancer Group A). Radium is a product of radioactive decay of naturally occurring uranium and thorium. Radium is also radioactive, and the decay of radium and its products is accompanied by alpha, beta, and gamma radiation (ATSDR, 2015).

5.5.1.12 pH

The pH exceeded the WY Class I Domestic standard and the EPA SDWR of 8.5 in the samples from PGDW05, PGDW20, PGDW23, PGDW30, and PGDW32. In other words, the water was too alkaline.

Excessively alkaline water has a slippery feel (i.e. feeling like soap doesn't rinse off), a soda taste, and will leave deposits.

5.5.2 Synthetic Organic Compounds Identified in Pavillion Area Groundwater

5.5.2.1 Bis(2-Ethylhexyl) Phthalate

Bis(2-ethylhexyl) phthalate was reported at concentrations greater than the MCL of 6 µg/L in one sample each from PGDW05, PGDW23, PGDW30, and PGDW41A, and in both the June and August 2014 samples from PGDW44. It was reported at concentrations greater than the MDL in 13 samples total. However, bis(2-ethylhexyl) phthalate was reported at concentrations greater than the MDL in both the June and August 2014 samples from only two water-supply wells: PGDW05 and PGDW44 (**Table 19B**). In samples collected by the US EPA in 2009 and 2010, bis(2-ethylhexyl) phthalate had reported concentrations greater than the MCL of 6 µg/L in samples from PGDW14, PGDW20, and PGDW41B. It was reported at concentrations greater than the MDL in five samples total (**Table 24C**). However, of the analyses performed by a second laboratory, reported bis(2-ethylhexyl) phthalate concentrations were less than the MDL in all but one of the EPA's samples (PGDW41B, January 2010, 7.4 J µg/L).

As discussed in Section 4, bis(2-ethylhexyl) phthalate is used as a plasticizer in flexible PVC plastics and is a common laboratory contaminant at concentrations less than 100 µg/L. Consequently, the reported concentrations of bis(2-ethylhexyl) phthalate may be an artifact of the laboratory analysis. Bis(2-ethylhexyl) phthalate also may be associated with materials present in the wells and distribution system. Flexible PVC also constitutes the inner and outer insulating jacket in non-metallic sheathed cable commonly used in house wiring and in submersible well pump cable.

Bis(2-ethylhexyl) phthalate is classified by the US EPA as a probable human carcinogen (i.e. Cancer Group B2, sufficient evidence in animals and inadequate or no evidence in humans).

5.5.2.2 Beta-BHC

In the groundwater sample collected from PGDW23 in August 2014, the organochlorine pesticide beta-BHC was reported at a concentration of 0.06 J µg/L, which was greater than the WY DWEL of 0.0499 µg/L (**Table 21**).

Beta-BHC is an isomer of the main component of the insecticide Lindane, gamma-BHC. Technical-grade Lindane, a mixture of 10 to 15 percent gamma-BHC plus other isomers (alpha-, and delta- as well as beta-BHC) was used as an insecticide in the United States up until about 1985. Lindane (gamma-BHC) in purer form is still imported for use in the United States as an insecticide and as a prescription medicine to treat scabies and head lice. All forms of BCH persist in the environment. The WY DWEL of 0.0499 µg/L is based on potential carcinogenicity. The US EPA has classified beta-BHC as a possible human carcinogen (ATSDR, 2005).

5.6 Other Organic Chemicals Reported at Concentrations Greater Than Method Detection Limits

5.6.1 Petroleum Hydrocarbons

As noted in Section 4, analyses for DRO and GRO are non-specific. Thus, in addition to dissolved constituents of petroleum, the methods will also report as DRO or GRO constituents such as: products of petroleum biodegradation, other chemicals (including chlorinated solvents), naturally occurring dissolved organic matter, byproducts of bacterial growth, and laboratory artifacts. Reported GRO and DRO concentrations greater than RL were qualified by laboratory as exhibiting a chromatographic pattern which did not resemble the petroleum standard with a Y. These results were qualified as estimated (J) during data validation.

Petroleum hydrocarbons such as DRO and GRO are a mixture of hundreds to thousands of individual compounds. Due to effective solubility differences, however, only a subset of these compounds are dissolved in groundwater at measurable concentrations. Fresh petroleum fuels such as DRO and GRO consist almost entirely of non-polar compounds. Polar compounds have an affinity for water and thus have greater solubility in water, whereas non-polar compounds have a greater affinity for oil and thus have lower solubility in water. Biodegradation of petroleum compounds in the environment produces polar metabolites, such as organic acids, esters, alcohols, aldehydes, phenols, and ketones. Therefore, relatively unweathered petroleum consists primarily of non-polar compounds, and weathered and biodegraded petroleum includes increasing proportions of polar compounds.

SGCU is a method of removing polar organic compounds from the sample while retaining the non-polar hydrocarbons. Thus, analytical results for DRO with SGCU represent the concentration of non-polar hydrocarbons, and are more representative of petroleum hydrocarbons.

Reported DRO concentrations with SGCU compared with reported DRO concentrations without SGCU in the groundwater samples collected in June and August 2014 reveals that in most cases, the reported DRO concentration with SGCU was less than the MDL (**Table 15**). This suggests that the reported DRO concentrations in many of the samples are attributable to, or were predominantly non-polar compounds.

Exceptions include the June and August 2014 samples from PGDW41B, where the reported DRO results with and without SGCU were similar. During previous sampling of PGDW41B

conducted by the EPA in January 2010, DRO (without SGCU) was reported at 850 and 479 µg/L in samples sent to two separate laboratories. Total extractable hydrocarbons (TEPH) were reported at 1,300 µg/L in this same sample (**Table 24C**). For that sampling event, the US EPA hired a local well service contractor to install a temporary pump and discharge line. Other reviewers of the US EPA reports have suggested that this work may have contributed to the reported DRO and TEPH results (NewFields, 2011).

Other reported DRO concentrations greater than the MDL in samples prepared with SGCU include both June and August 2014 samples from PGDW05 (26 J and 31 J µg/L) and the June 2014 sample from PGDW30 (21 J µg/L). In the June 2014 samples collected from PGDW45, DRO was reported at a concentration 33 J µg/L in the primary sample, but was reported at less than the MDL of 16 µg/L in the duplicate sample. GRO was reported above the MDL in the June 2014 samples from PGDW05 and PGDW45, but not in the August 2014 samples from these wells (**Table 15**).

5.6.2 Petroleum and Fuel Constituents

Isopropyl benzene was reported at 0.1 J µg/L in the June (primary and duplicate) and August 2014 groundwater samples from PGDW32; also, tertiary butyl alcohol (TBA) was reported at a concentration of 2.0 J µg/L in the June 2014 duplicate sample from this well, but not in the other two samples (**Table 16A**). Isopropyl benzene is a constituent of petroleum and gasoline (API, 1994). When released into the environment, compounds such as isopropyl benzene (alkyl benzene compounds with larger branched substituents) are more slowly degraded than many other constituents of gasoline (Chapelle, 2001). TBA was used as an additive to gasoline. In analyses of produced natural gas samples collected from gas wells in 2010, isopropyl benzene was reported at concentrations between approximately 542 and 3,430 µg/L (US EPA, 2010).

Though PGDW32 is 675 ft deep, the surface casing is 30 ft deep (**Table 2**); it is also within 576 ft of the reported location of the pit for gas well Tribal Pavillion 12-13. Also, the insecticide Lindane was reported in the groundwater June 2014 groundwater samples obtained from this well (**Table 24A)**. Thus, the groundwater in PGDW32 shows possible impacts from surface releases, and the isopropyl benzene may be from multiple possible sources: surface releases of either gasoline or unrefined petroleum, or migrating gas.

The reported human odor threshold for isopropyl benzene ranges from 0.008 to 0.012 ppm in air (NIH, 2015).

Naphthalene was reported in the June 2014 samples from PGDW14 (0.6 J µg/L) and PGDW44 (0.2 J- µg/L) but not in the August 2014 samples (**Table 16A, Table 24A**). Naphthalene is a component of petroleum, gasoline and distillate fuels (API, 1994). In analyses of produced natural gas samples collected in 2010, naphthalene was reported as not detected (US EPA, 2010).

The reported human odor threshold for naphthalene is 21 µg/L in water (NIH, 2015).

5.6.3 2-Butoxyethanol

2-butoxyethanol was reported at an estimated concentration of 3,100 J µg/L in the June 2014 sample collected from PGDW33 (**Table 17**). However, the reported concentration was near the MDL of 2,300 µg /L, and the analytical method employed (US EPA 8015A) uses a non-specific detector, so compound identification is less certain.

2-butoxyethanol is a widely used chemical. Industrial uses include flame retardants, paint and coating additives, and solvents for cleaning/degreasing. Consumer uses include anti-freeze and de-icing products, cleaning products, lubricants, paints and coatings, and personal care products (NIH, 2015). It is used as a surfactant in hydraulic fracturing fluids (Llewellyn et al, 2015).

PGDW33 is shallow, with a total depth of 30 ft (**Table 2**), and two domestic septic systems are located within approximately 250 and 300 ft. Thus, if present, potential sources of the 2-butoxyethanol reported in the sample from PGDW32 include the septic systems and surface releases.

5.6.4 Pyruvic Acid

Pyruvic acid is a naturally occurring organic acid that is an intermediate in the metabolism of sugar and in the degradation of carbohydrates. It is widely present in living organisms (NIH, 2015). It was reported at a concentration of 2,060 µg/L in the August 2014 groundwater sample from LD02. Its presence is attributable to the apparent biological growth in the sample, which was described as brownish-black with some yellowish-green particulate matter present in agglomerations less than 1 centimeter across (**Appendix P**).

5.6.5 Pesticides

In addition to the organochlorine insecticide beta-BHC, discussed above in Section 5.7.2.2, four other organochlorine insecticides were reported in groundwater samples from the water-supply wells: Endosulfan I, Endosulfan II, gamma-BHC or Lindane, and heptachlor (**Table 24A** and **Table 24C**). However, these pesticides were not consistently reported at concentrations greater than the MDL from one sampling event to the next, and when greater than the MDL were less than the RL or otherwise qualified as estimated (J).

5.6.6 Other Volatile Organic Compounds

Carbon disulfide was reported at concentrations greater than the MDL but less than the RL in three groundwater samples: the August 2014 sample from LD02 (0.2 J- µg/L), the August 2014 sample from PGDW20 (0.3 J- µg/L), and the June 2014 sample from PGDW30 (0.1 J µg/L) (**Table 16**).

Adamantane and 1,3-dimethyladamantine were reported in the January 2010 samples (primary and duplicate) obtained by the US EPA from PGDW05. Adamantane was also reported in the January 2010 sample from PGDW32, and 1,3-dimethyladamantane was reported in the January

2010 sample from PGDW30. Reported concentrations in groundwater ranged up to 1.81 J µg/L 1,3-dimethyladamantane in the sample from PGDW30 (**Table 24C**).

Adamantanes have been recognized as a petroleum component since the early 1930s. In produced natural gas samples analyzed by the US EPA in 2010, reported adamantine concentrations ranged from less than the RL to 74,000 µg/L, and reported 1,3-dimethyladamantine concentrations ranged from less than the RL to 9,800 µg/L (US EPA, 2010). Therefore the source of the adamantanes in the water-supply wells may be from naturally occurring gas.

5.6.7 Other Semivolatile Organic Compounds

Samples collected by the US EPA in 2010 were analyzed for tris(2-butoxyethyl)phosphate, or tributoxyethanol phosphate. Concentrations greater than the MDL were reported in samples from PGDW05 (0.56 J µg/L, duplicate sample only), PGDW20 (0.63 J µg/L), PGDW42 (0.55 J µg/L), PGDW44 (1.16 J µg/L), and PGDW49 (0.57 J µg/L). Tributoxyethanol phosphate is part of a class of chemicals known as phosphate esters, which are used as flame retardants and hydraulic fluids. This chemical is also used as a solvent, and is incorporated into consumer products, such as lubricants, paints and coatings, and plastics and rubber (NIH, 2015; ATSDR, 2015).

In the samples collected by the US EPA in 2010, caprolactam was reported at concentrations greater than the MDL in 6 samples, at estimated concentrations ranging up to 1.4 J µg/L. The primary use of caprolactam is the manufacturing of fibers, especially Nylon 6. It is also used as a plasticizer and a cross-linker for polyurethane (NIH, 2015).

5.6.8 Tentatively Identified Compounds

Tert-butyl iodide was reported at a concentration of 5.3 J in the June 2014 sample obtained from PGDW05, but was not identified in the August 2014 sample.

In the June 2014 sample collected from PGDW05, Z-9-octadecenamide was reported at 6.7 J µg/L. This compound is also known as (Z)-octadec-9-enamide, oleamide, and oleic acid amide. It has a large molecular weight, consisting of a chain of 18 carbon atoms terminated by an amide group. Industrial uses include adhesives, sealants, adsorbents, lubricants, and lubricant additives. Consumer uses include lawn and garden care products, lubricants, and greases (NIH, 2015).

In the June 2014 sample obtained from PGDW20, an unknown compound was reported at a concentration of 4.9 J µg/L. In the August 2014 sample from PGDW20, 2-[2-[4-(1,1,3,3-tetramethylbutyl)phenoxy]ethoxy] ethanol was reported at 18 J µg/L, heneicosane was reported at a concentration of 4 J µg/L, p-tert-amyl phenoxy ethanol was reported at a concentration of 10 J µg/L, and seven unknown compounds were reported at concentrations between 4 J and 180 J µg/L.

2-[2-[4-(1,1,3,3-tetramethylbutyl)phenoxy]ethoxy] ethanol, also known as 4-tert-octylphenol diethoxylate, is one of a class of compounds known as octylphenol ethoxylates (OPEs). OPEs are surfactants incorporated into detergents and industrial cleaners, and are used as emulsifiers or

wetting agents in products, such as paints, pesticides, and personal care products (CDC, 2015). They are part of a larger group of chemicals known as alcohol ethoxylates or ethoxylated alcohols, which are of the broader general category of non-ionic surfactants. OPEs of varying molecular weights are produced to tailor the properties of the product. For example, mixtures of ocytyphenol ethoxylates with an average of 1.5 to 3 ethoxy and ethanol groups are marketed by Dow Chemical as Triton X-15 and Triton X-35, respectively, and act as oil-soluble emulsifiers and rinse aids. They are utilized as defoamers, dye solubilizers, and dry cleaning (Dow Chemical, 2015). In the list of chemicals used by natural gas producers in the Pavillion Gas Field, alcohol ethoxylates are listed as "alcohols, C6-10, ethoxylated", "ethoxylated alcohol linear" (listed as 1 to 3, 10 percent of product), "oxylated alcohol" (30 percent of product), and "ethoxylated alcohol" (1-3 percent of product) (WDEQ, 2007). Alcohol ethoxylates are also listed in the TEDX inventory of chemicals used in oil and gas production (US EPA, 2010).

P-tert-amyl phenoxyethanol, or 2-(p-tert-amylphenoxy) ethanol is also an ethoxylated alcohol. Heneicosane is a straight-chain alkane containing 21 carbon atoms.

Unknown compounds were reported in the following samples: LD02, August 2014, PGDW41A, August 2014, and PGDW41B, June and August 2014. The estimated concentration of unknown compounds in these samples was 37 µg/L or less (**Table 19C**).

5.6.9 Other Compounds which May Be Analytical Artifacts

As discussed in Section 4, reported concentrations of acetone, methylene chloride, and 2-propanol may be artifacts of analysis. Acetone and methylene chloride are known as common laboratory contaminants (US EPA, 1991); isopropanol was frequently reported at concentrations greater than the MDL in the trip blank samples (15 of 20 trip blank samples). Phthalates are recognized as common laboratory contaminants when reported at concentrations less than 100 µg/L (US EPA, 2014).

5.7 Geochemical Changes from Biodegradation of Dissolved Organic Compounds and Effects on Water Quality and Palatability

5.7.1 Microbial Biodegradation of Organic Compounds and Geochemical Evolution

5.7.1.1 Biogeochemical Evolution of Groundwater

Microorganisms are ubiquitous in groundwater systems, and bacteria in particular are central to understanding the geochemical evolution of groundwater. One major process of biogeochemical evolution of groundwater is the biodegradation of dissolved organic compounds (DOC). The biogeochemical changes may be viewed in terms of oxidation-reduction (redox) processes, where the dissolved organic compounds constitute the electron donor, and where dissolved oxygen, nitrate, manganese, iron, and sulfate constitute the electron acceptors. The redox half reaction involving the electron acceptor (e.g. oxidation, nitrate reduction) may be referred to as the terminal electron acceptor process, or TEAP. The sequence of biodegradation generally follows the most energetically-favorable pathways in this order: oxidation (or aerobic biodegradation), followed by anaerobic biodegradation, including nitrate reduction, manganese

reduction, iron reduction, finally sulfate reduction, and ultimately, methanogenesis (Chapelle, 2001; Clark, 2015). Using CH_2O to represent DOC in general, the sequence biogeochemical evolution is, in order of decreasing energy yield:

$CH_2O + O_2 \rightarrow CO_2 + H_2O$
$CH_2O + 4/5NO_3- + 4/5H+ \rightarrow 2/5N_2 + CO_2 + 7/5H_2O$
$CH_2O +2MnO_2 +4H+ \rightarrow CO_2 +2Mn^{2+} +3H_2O$
$CH_2O + 4Fe(OH)_3 +8H+ \rightarrow CO_2 +4Fe^{2+} + 11H_2O$
$CH_2O + SO_4^{2-} \rightarrow H_2S + 2HCO_3-$
$2CH_2O \rightarrow CH_4 + CO_2$ (methanogenesis involves multiple steps of fermentation, acetogenesis, and acetate fermentation and/or CO_2 reduction)

Immediate products of the redox reactions include dissolved carbon dioxide, soluble manganese, soluble iron, and hydrogen sulfide. Whether these products persist in the groundwater system depends partly on both the chemical composition of the aquifer sediments and the relative abundance of other redox products. For example, in the presence of hydrogen sulfide and high pH, dissolved ferrous iron will precipitate as amorphous black iron sulfide, mackinawite (FeS). Similarly, high dissolved inorganic carbon concentrations (DIC, primarily carbonate and bicarbonate) will also control ferrous iron solubility, leading to the precipitation of siderite ($FeCO_3$) (Clark, 2015). Similarly, depletion of electron acceptors is not always observed in groundwater systems, and thus does not constitute evidence that biodegradation is not occurring, because sources are present in the aquifer sediments or adjacent confining beds. For example, many sedimentary aquifers or adjacent aquitards contain gypsum, which acts as a source of sulfate (Chapelle, 2001).

5.7.1.2 Results of Sampling for Microorganisms

Iron-related bacteria were reported in both the June and August 2014 samples collected from LD02, PGDW14, PGDW41B, and PGDW44; they were reported in one sample from PGDW05, PGDW32, PGDW33, PGDW41A, and PGDW45 (duplicate sample collected in June 2014 only). Sulfate-reducing bacteria were reported in both the June and August 2014 samples collected from PGDW44; they were reported in one sample from PGDW30, PGDW32, PGDW33, PGDW41A, PGDW41B, and PGDW49 (primary sample collected in August 2014 only) (**Table 26A**).

A subset of the groundwater samples collected from PGDW05 from April 2005 through October 2008 was analyzed for iron-reducing bacteria, slime-forming bacteria, sulfate-reducing bacteria, and heterotrophic bacteria (April 2005 sample only). Bacteria were reported present in all samples except one identified as being collected from inside the residence (**Table 26B**).

In samples collected by the US EPA in 2009 and 2010, heterotrophic and iron-related bacteria were reported in samples from PGDW05, PGDW23, PGDW41B, PGDW42, PGDW44, and PGDW49 (**Table 26C**). Iron-related bacteria were reported in the sample from PGDW45.

Sulfate-reducing bacteria were reported in the samples from PGDW05, PGDW30, PGDW41B, PGDW44, PGDW45, and PGDW49.

Results of bacterial counts in groundwater are variable; this includes some instances where bacteria are reported in one sample out of a pair of primary and duplicate samples (**Tables 26A** and **26B**). The bacterial counts for iron-related bacteria and sulfate-reducing bacteria are derived from BART tests, which rely on visual inspection of culture medium; therefore, they should be considered semi-quantitative results. This may explain at least part of the variability in the reported counts. Some of the variability may also be attributable to sampling and conditions inside the well, and whether or not bacteria detached from the surfaces upon which they were growing. Results for iron-related and sulfate-reducing bacteria are summarized below:

Location	Iron Related Bacteria						Sulfate Reducing Bacteria					
	2005-2008	Mar-09	Jan-10	Jun-14	Aug-14	Maxi-mum	2005-2008	Mar-09	Jan-10	Jun-14	Aug-14	Maxi-mum
LD02	-	-	-	Y	Y	50,000 J	-	-	-	N	N	-
PGDW05	7Y	Y	Y	N	Y	14M	7Y	Y	Y	N	N	500,000
PGDW14	-	-	-	Y	Y	50,000	-	-	-	N	N	-
PGDW20	-	N	N	N	N	-	-	N	N	N	N	-
PGDW23	-	N	Y	N	NN	230,000	-	N	N	N	NN	-
PGDW30	-	-	N	N	N	-	-	-	Y	N	Y	20,000 J
PGDW32	-	-	N	NN	N	-	-	-	N	NN	Y	20,000
PGDW33	-	-	-	Y	N	50,000 J	-	-	-	Y	N	120,000 J
PGDW41A	-	-	-	N	Y	230,000	-	-	-	N	Y	500,000
PGDW41B	-	-	Y	Y	Y	230,000	-	-	Y	Y	N	120,000 J
PGDW42	-	-	Y	-	-	50,000	-	-	N	-	-	-
PGDW44	-	-	Y	Y	Y	50,000	-	-	Y	Y	Y	120,000 J
PGDW45	-	-	Y	YN	N	900,000	-	-	Y	NN	N	100 – 1,000
PGDW49	-	-	Y	Y	YN	3.6M	-	-	Y	N	YN	1M - 10M

Notes:
Y = present.
N = absent.
M = million.
Double letters indicate results for primary and duplicate samples.
PGDW05 sampled seven times from 2005 to 2008.

The data indicates that iron-related bacteria are present in groundwater obtained from the water-supply wells included in the study, except for PGDW20, PGDW30, and PGDW32. Results are less definitive for PGDW23, with one positive result out of five samples.

Sulfate-reducing bacteria appear to be present in groundwater obtained from PGDW05, PGDW30, PGDW33, PGDW41A, PGDW41B, PGDW44, and PGDW49. Results for sulfate-reducing bacteria are less definitive for PGDW32 and PGDW45, with one positive result out of four samples obtained from each well.

5.7.1.3 Microbial Activity Inferred from Visual Condition of Well Casings

Results from the video surveys also indicate the presence of bacteria and/or the associated mineral precipitation. Extensive encrustation and scaling was observed in PGDW05 and PGDW49 (**Table 3**); samples from these wells contained the greatest bacterial counts. Bulbous concretions were reported on the casing of PGDW44. Extensive encrustation was also reported in PGDW20, which is apparently contrary to the sample results for microorganisms. Extensive encrustation was not reported in the wells constructed with PVC casings (LD02, PGDW23, PGDW41A, and PGDW41B), because PVC is not subject to bacterially-moderated redox reactions, as opposed to the iron in steel casing. Video surveys at LD02, PGDW20, PGDW23, PGDW41A, PGDW41B, and PGDW44 did not extend into the screened portion of these wells, so observations could not be made at locations where the effects of bacterial growth and mineral deposition are typically greatest.

5.7.1.4 Inferred Redox State of Groundwater from Water-Supply Wells

Analytical data from samples obtained from the water-supply wells may provide indication of the redox state of the groundwater; however, interpretation is complicated by effects of the well construction and sampling. As discussed in Section 4, these effects include frequent pumping (with accompanying induced changes in groundwater chemical characteristics), and screened or perforated intervals which may intersect multiple separate permeable intervals (with differing groundwater chemistry). LD02 is collapsed above the screened interval, so the extent that the samples represented ambient groundwater versus static water in the well casing is unknown; therefore, results for samples from this well are not considered further in this section. Other potential factors include the pressure tanks at PGDW05, PGDW20, PGDW30, PGDW33, PGDW41A, and PGDW41B; and the distance of PGDW20 and PGDW33 from the sampling point.

In most groundwater samples obtained in June and August 2014, measured dissolved oxygen concentrations were less than 0.5 mg/L (**Table 11**). At concentrations below 0.5 mg/L, oxidation is no longer the predominant TEAP (Chapelle, 2001). Exceptions include the following, with dissolved oxygen concentrations measured in June and August 2014 provided:

- PGDW30: 1.23 and 0.71 mg/L. Downstream of pressure tank.
- PGDW33: 0.99 and 4.29 mg/L. The production rate of this shallow well (TD 30 ft bgs) is low, and it is equipped with a jet pump. Thus, aeration of the sample may have occurred. Downstream of pressure tank.
- PGDW41A: 7.35 and 0.91 mg/L. The dissolved oxygen concentration of 7.35 mg/L measured in the sample collected in June 2014 was an apparent consequence of air entrainment when the water level was drawn down to the pump intake before sampling. In August, the well was purged at a low rate (approximately 3 gpm), but sample aeration cannot be ruled out. Downstream of pressure tank.
- PGDW45: 1.16 and 1.4 mg/L. This is a shallow well, with a total depth of 48 ft bgs.

- PGDW49: 0.56 and 1.55 mg/L. Based on dissolved oxygen readings, the water level may have approached the pump intake in this shallow well during sampling (TD 50.7 ft bgs).

In the June and August 2014 groundwater samples, nitrate was reported at concentrations greater than 0.5 mg/L in samples from: PGDW33, PGDW41A, PGDW45, and PGDW49. This indicates that nitrate reduction is still occurring in the groundwater produced by these water-supply wells. Results are summarized below with nitrate concentrations measured in June and August 2014 provided:

- PGDW33: 3.2 and 2.0 mg/L. This shallow well (TD 30 ft bgs) may receive shallow recharge with dissolved nitrate.

- PGDW41A: 21 and 17 mg/L. These are the greatest reported nitrate concentrations in the samples collected in June and August 2014, and exceed the EPA MCL and WY Class I standard for nitrate. As discussed above, the general water chemistry differs from the other water-supply wells, in that chloride constitutes approximately 20 to 25 percent of the anions (**Figure 16A**).

- PGDW45: 2.0 and 1.7 mg/L. This is a shallow water-supply well, with a total depth of 48 ft bgs.

- PGDW49: 6.0, and 4.4 and 4.3 mg/L (latter values for primary and duplicate samples. This is a shallow water-supply well with a total depth of 50.7 ft bgs.

As discussed above, the groundwater in shallow water-supply wells PGDW33 and PGDW45 appears to be influenced by infiltration. Water from shallow water-supply well PGDW45 is predominantly calcium bicarbonate; the predominant cation in the water from shallow water-supply well PGDW33 is calcium and it has the second-highest proportion of bicarbonate (**Figure 16A**). The pH of groundwater from these two wells is also the lowest and is near neutral, and the TDS concentrations also exhibit apparent seasonal variation.

Concentrations of ferrous iron and dissolved manganese indicate that iron reduction and manganese reduction were occurring at PGDW41B and PGDW44. In groundwater samples collected in June and August 2014, measured ferrous iron concentrations and reported dissolved iron concentrations were greatest in samples obtained from PGDW41B and PGDW44. Reported dissolved manganese concentrations were also greatest in samples obtained from these wells:

- PGDW41B: Ferrous iron 0.73 and 0.74 µg/L; dissolved iron 0.56 and 0.55 mg/L; dissolved manganese 0.16 and 0.17 mg/L.

- PGDW44: Ferrous iron 2.26 and 3.3 mg/L; dissolved iron 2.4 and 3 mg/L; dissolved manganese 0.3 and 0.29 mg/L.

Reported concentrations of sulfide in the groundwater samples collected in June and August, 2014 were variable and were qualified as estimated. The greatest sulfide concentrations were reported in samples from PGDW20 (50 J- mg/L, June 2014), PGDW32 (90 J- and 60 J- mg/l,

June 2014 primary and duplicate samples), PGDW33 (40 J- mg/l, August 2014), and PGDW44 (40 J- mg/l, June 2014).

Under reducing conditions, the presence of hydrogen sulfide will greatly limit the solubility of ferrous iron. Under conditions except high pH, ferrous iron will precipitate as amorphous iron sulfide (Clark, 2015). Thus, once redox conditions transition from manganese and iron reduction to sulfate reduction, measurable concentrations of iron will no longer be present in the groundwater.

5.7.1.5 Isotopic Evidence of Nitrate Reduction

Stable isotopes of nitrogen and oxygen in nitrate may be used as indicators of the source of nitrate in agricultural areas. Industrial nitrogen fertilizer such as ammonium is produced from atmospheric gas so the value of nitrogen-15 is near 0 ‰ (parts per thousand). Nitrate from urea involves mineralization from soil water which is depleted in oxygen-18; thus, nitrate from most chemical fertilizers has δ15N and δ18O values near 0‰. Subsequent denitrification will result in enrichment of both nitrogen-15 and oxygen-18. Nitrate from human or animal wastes is somewhat enriched in nitrogen-15 to approximately 5‰ to 10‰ or greater (Clark, 2015).

Stable isotope data for nitrogen-15 and oxygen-18 in nitrate indicate that groundwater from PGDW41A and PGDW45 is enriched in the heavier isotopes, with δ15N values of approximately 30 and 40‰, respectively, and 18O values of approximately 10 and 15‰, respectively (**Table 27**). This indicates that the groundwater has undergone denitrification. The δ15N values of approximately 30 and 40‰ suggest a source of human or animal waste (δ15N approximately 5‰ to 10‰) that was subsequently enriched. Stable isotope data suggest that nitrate reduction may also be occurring at PGDW33 and PGDW45, though the degree of enrichment of heavier isotopes is less.

5.7.1.6 Summary of Observations Related to Biogeochemistry

Results of analyses of water chemistry and microorganisms and qualitative observations of the apparent condition of the well casings are summarized below. The inferred groundwater redox condition is based on the presence and absence of electron acceptors.

Location	Iron Related Bacteria	Sulfate Reducing Bacteria	Well Casing: Heavy Encrustation or Scaling	Groundwater Redox Conditions Inferred from Electron Acceptors	Isotopic Indicators
PGDW05	Present	Likely present	Yes	In range of manganese to sulfate reduction	-
PGDW14	Present	Not active	-	In range of manganese to sulfate reduction	-
PGDW20	Not active	Not active	Yes	Sulfate reduction	-
PGDW23	Less likely present	Not active	No, PVC *	In range of manganese to sulfate reduction	-
PGDW30	Not active	Likely present	-	Possibly oxygen reduction	-

PGDW32	Not active	May be present	-	Sulfate reduction	-
PGDW33	May be present	May be present	-	Nitrate reduction/sulfate reduction	Possible nitrate reduction, 15N and 18O may be enriched
PGDW41A	May be present	May be present	No, PVC *	Nitrate reduction	Nitrate reduction 15N and 18O enriched
PGDW41B	Present	Likely present	No, PVC *	Iron and manganese reduction	-
PGDW44	Present	Present	Not heavy *	Iron and manganese reduction/sulfate reduction	-
PGDW45	May be present	May be present	-	Oxygen and nitrate reduction	Possible nitrate reduction, 15N 18O may be enriched
PGDW49	Present	Likely present	Yes	Nitrate reduction	Nitrate reduction 15N and 18O enriched

Note:
** = Video survey did not extend into screened portion of the well.*
PVC = Well constructed with PVC casing.

In summary, inferred biogeochemical conditions in the water-supply wells range from oxygen reduction to sulfate reduction. In many instances, the indicators are mixed, such as sampling results for microorganisms that are associated with a different redox state than implied by the data for electron acceptors. The apparent inconsistencies may be attributable to well construction where the water-supply well intercepts groundwater from multiple permeable zones with different geochemical conditions. Apparent differences may also arise from temporal changes in water quality or variability associated with obtaining groundwater samples from water-supply wells. Some general conclusions are:

- The shallowest water-supply wells (PGDW33, PGDW41A, PGDW45, and PGDW49) show indications of nitrate reduction, and also oxygen reduction in data from PGDW45, based on sampling results for electron acceptors and stable isotopes. This is consistent with general geochemical signatures discussed above for PGDW33 and PGDW45 that are associated with shallow groundwater influenced by surface water infiltration.

- Groundwater samples from the deeper wells indicate a range of more reducing conditions with the exception of PGDW30.

5.7.2 Water Quality and Palatability Effects

The presence of hydrogen sulfide in groundwater imparts a characteristic odor commonly associated with rotten eggs. It can be detected in water at concentrations on the order of tens of µg/L, and at less than 0.01 part per million by volume (Hem, 1985; Chapelle, 2001; Clark, 2015).

As discussed above, other constituents with concentrations greater than water-quality standards have known palatability effects. These constituents are naturally occurring, and include sodium, sulfate, and TDS. The taste threshold for sodium varies with the associated anion, with the average taste threshold around 200 mg/L, including sodium chloride (table salt). Water with

excessive sulfate concentrations (greater than 250 mg/L) will have a bitter or astringent taste. As TDS concentrations increase to greater than 1,000 mg/L, drinking water becomes increasingly unpalatable (WHO, 2011).

5.7.3 Gas Hydrocarbons and Microbial Biodegradation

Biodegradation of petroleum hydrocarbons in groundwater is a ubiquitous and widely-recognized process. Both aerobic and anaerobic biodegradation are widely documented. Engineered bioremediation systems along with monitoring of naturally occurring biodegradation ("monitored natural attenuation") are standard approaches to the remediation of petroleum hydrocarbons in groundwater (ASTM, 2015; Fetter, 1993; Chapelle, 2001)

Natural gas, including gas produced from the Pavillion Gas Field, consists primarily of methane plus short carbon-chain alkanes (ethane, propane, isobutene, and n-butane). The ratio of methane to ethane plus propane (C1/ C2+C3) is between approximately 10 and 40 (**Figure 16A**). In five produced gas samples analyzed by the US EPA in 2010, the approximate composition was as follows, in weight percentage: methane 75-85, ethane 6-7, propane 1-3, isobutane <1 to 2, and n-butane <1 to 2. Aerobic biodegradation of methane and alkanes proceeds readily, though methane oxidation involves a specialized enzyme system. Although generally focused on aromatic hydrocarbons, numerous studies have demonstrated the anaerobic biodegradation of petroleum constituents (Chapelle, 2001).

In a study of methane seepage into a shallow groundwater aquifer from an inactive oil production well in Alberta, evidence for bacterial sulfate reduction of methane was reported. In conjunction with spatial and temporal changes in methane and sulfate concentrations in groundwater, indicators included isotopic enrichment of sulfur and oxygen in sulfate, and isotopic trends of carbon in bicarbonate, a product of the sulfate reduction of methane (Van Stempvoort et al., 2005).

Similar biogeochemical changes were observed in a study of groundwater quality following a gas well blowout in Ohio (Kelley et al., 1985). Following the blowout, well owners reported water-quality problems, including an intense sulfide odor in the water, increased iron, and black precipitate. Concentrations of iron and manganese were greatest in groundwater samples collected from water-supply wells with active gas bubbling, whereas nitrate concentrations were highest in "control" wells with no indications of methane impacts. The groundwater data indicated that the main biogeochemical reaction involving methane was sulfate reduction. In a related microcosm study, the addition of methane to groundwater resulted in an increase of sulfide concentrations of approximately eight orders of magnitude in 20 days.

Conditions in the Pavillion Gas field likely produces similar changes in groundwater quality. Microbial biodegradation of gas, which may be present due to seepage along gas wells and/or natural upward migration, can proceed to sulfate reduction, with associated changes in groundwater quality and palatability.

5.7.4 Dissolved Petroleum Hydrocarbons and Microbial Biodegradation

Biodegradation of petroleum hydrocarbons in groundwater from other sources such as surface releases of fuel or petroleum-based drilling fluids may lead to similar changes in groundwater quality. In the case of pits, the presence of inorganic drilling fluid additives or produced brines may also lead to increased concentrations of inorganic constituents, particularly chloride and TDS. However, as discussed in Section 5.4.4 above, the existing data are insufficient to determine if there is a spatial correlation between pits and pit-containing constituents in groundwater from nearby water-supply wells.

5.8 Treatment Options for Water-Quality Issues

The information below is provided to assist the homeowner with identifying potential treatment options for their water-well based on the constituents identified in the well.

5.8.1 Overview

The following table summarizes the problematic water quality constituents in the water-supply wells included in the study and the potentially applicable treatment technologies.

Water Quality Constituent(s)	Potentially Applicable Technology								
	Acidulation	Aeration	Carbon Adsorption	Chlorination	Filtration	Greensand Adsorption	Ion Exchange	Ozonation	Reverse Osmosis
Turbidity					X				
Elevated pH	X								
Total Dissolved Solids							X		X
Sulfate							X		X
Sodium							X		X
Iron and Manganese						X	X		X
Chloride							X		X
Nitrite							X		X
Trace Metals (Arsenic, Lithium, Thallium, Uranium)							X		X
Pesticides			X						
Radionuclides (Radium)							X		X
Radon-222		X	X						
Microorganisms				X				X	

The potentially applicable water treatment technologies are discussed below.

<u>Acidulation (treatment for elevated pH)</u>

Acidulation involves the addition of acid to water to decrease pH. Either a strong acid (hydrochloric, sulfuric) or weak acid (white vinegar) can be used depending on the magnitude of the pH decrease required and the buffering capacity of the water (the resistance to pH change because of the presence of certain minerals). A metering pump typically injects acid from a storage tank into the piping at point of entry into the residential water system. Acidulation is the most direct and inexpensive method to decrease pH. The potential drawbacks are the safety issue of handling acid (especially a strong acid) and damage to the water system that would be caused by overtreatment. A system using a metering pump would have automatic pH monitoring

installed to prevent overtreatment. Although not preferred from a safety standpoint, hydrochloric acid is freeze-resistant compared to the other acids.

Aeration (treatment for radon-222)

Aeration typically involves injecting air into the water to strip out the volatile constituents, but can also be accomplished (less efficiently) by pumping water into the headspace of a non-pressurized vented storage tank. Commercially available package units for aeration may use either method, but in any case, aeration requires a vented storage tank between the wellhead and point of entry to allow the volatile constituents (and injected air) to escape the water system. Aeration may also remove iron by oxidizing the soluble ferrous iron to insoluble ferric iron, but this process generates a solid iron waste; therefore aeration is not considered in this analysis as an iron removal technology. The potential generation of solid waste in water containing elevated iron is a drawback for use of aeration for removal of volatile constituents.

Carbon Adsorption (treatment for pesticides and radon-222)

Carbon adsorption involves passing water through a vessel containing granular activated carbon (GAC), which adsorbs the contaminants from the water. When the GAC is loaded with contaminants to the point that "breakthrough" occurs, the spent GAC is removed from the vessel and replaced with fresh GAC. A common practice in carbon adsorption treatment is to operate with two vessels, a primary and secondary, where the secondary vessel serves to adsorb breakthrough contaminants from the primary vessel until the GAC in the primary vessel can be replaced. GAC can be efficient at removing pesticides and radon-222 from water, but GAC also has a limited capacity to adsorb many other impurities, including various anions, cations, and metals. Water with an elevated TDS content can significantly decrease the GAC vessel breakthrough time for the target contaminants compared to water without elevated TDS. For radon-222, the US EPA recommends not treating feed water with a concentration greater than 5,000 µg/L to preclude hazardous accumulation of radioactive radon and radon decay products in the carbon vessel.

Chlorination (treatment for microorganisms)

Chlorination (also called disinfection) involves the addition of chlorine gas or a chlorine-containing compound to destroy microorganisms (bacteria) in water. One method of chlorination is short-term (one-day) treatment of a well with a relatively high dose of a chlorine compound such as bleach, a process known as shock treatment. If the shock treatment cannot adequately disinfect the well, then a point of entry chlorination system can be installed. For residential water systems, bleach is typically the disinfectant compound of choice because of greater safety compared to the use of chlorine gas. A residential point of entry chlorination system typically has a bleach storage tank, and bleach is injected into the water as it is pumped from the well. Where freeze protection for the bleach storage tank is an issue, chlorine gas can be injected from a cylinder into the water line. Chlorination is a proven technology and the equipment and operating costs are relatively inexpensive. Elevated water pH decreases chlorination efficiency – local groundwater may need acidulation for effective chlorination. Feed water with an elevated

soluble ferrous iron content would need iron removal before or filtering after chlorination, as the chlorine chemicals will oxidize the ferrous iron to insoluble ferric chloride which would foul the water system.

Filtration (treatment for turbidity, insoluble iron)

Filtration is a simple and relatively inexpensive technology for removal of particulate matter that contributes to water turbidity. Filtration will also remove non-soluble (ferric) iron. In residential applications, filtration involves passing water through a cartridge or bag inside of a filter housing, where the filter material traps or blocks the particulate matter. The filter is replaced once loaded with particulate matter to the point that water flow is restricted. Filtration may not be completely effective at reducing turbidity, as turbidity can be mostly caused by particles less than 0.5 microns in diameter which may pass through even the most efficient cartridge and bag filters. In municipal water treatment, chemicals are added to the water to react with the particulate matter to create larger particles that are more amenable to effective filtration, but such a process is not practical for the relative small scale of a residential water system.

Greensand Adsorption (treatment for iron and manganese)

Greensand is a material with the unique capability to oxidize dissolved iron and manganese to their insoluble (solid) forms. The solid iron and manganese are then filtered (adsorbed) by the greensand. Treatment proceeds until the solid iron and manganese loading on the greensand restricts continued water flow, at which point the greensand vessel is backwashed similar to the process for a conventional residential water softener. Greensand adsorption is effective and relatively inexpensive. The major drawback is the hazard of the potassium permanganate (strong oxidizer chemical) used to backwash and regenerate the greensand.

Ion Exchange (treatment for TDS, anions, cations, metals, radionuclides)

Ion Exchange (IX) vessels contain resins manufactured to adsorb specific constituents. As water flows through an IX vessel, components on the surface of the resin switch (exchange) with the target constituents in the water. The conventional residential water softener is an example of an IX treatment in which the calcium and magnesium hardness minerals in the water exchange with sodium ions on the resin. When the sodium ions on the resin are depleted, the resin is backwashed with a salt (sodium) solution to regenerate the resin for another cycle of use. IX resins can be effective for numerous water constituents and many resins are regenerated with a salt solution that is inexpensive and safe to handle. However, some resins including those for sodium and chloride treatment require regeneration using a strong acid or caustic solution.

Ozonation (treatment for microorganisms)

Ozonation is an alternative to chlorination for water disinfection. In this technology, an ozone generator converts oxygen in the air to oxidizing ozone molecules and the ozone is injected into the water. Ozonation efficiency is relatively insensitive to water pH, so local groundwater ozonation has the advantage of not requiring feed water acidulation as necessary for chlorination.

However, ozone equipment is costly and ozone generation has a relatively high power requirement.

Reverse Osmosis (treatment for TDS, anions, cations, metals, radionuclides)

Reverse osmosis (RO) is conceptually similar to filtration in that water is pumped through a membrane, the difference being that in RO the membrane does not capture impurities like a filter element but rejects impurities along with a portion of the water. Thus, an RO unit has an inlet stream, a purified outlet stream, and a brine outlet waste stream containing a portion of the inlet water with most of the impurities. RO is an effective technology for removal of nearly all undesirable constituents from water, and does not require the backwash operation associated with depleted IX resin. However, RO has the drawbacks of relatively high equipment cost along with waste of roughly half of the feed water depending on the specific equipment. RO units also have relatively high energy usage as the feed water must be pressurized to 120 to 150 pounds per square inch to force water through the membrane. RO membranes can also be a maintenance problem as they are susceptible to fouling. Despite the drawbacks, the purification effectiveness of RO can make this an attractive treatment technology. For water of elevated pH, RO also has the benefit of decreasing pH by removing alkaline constituents from the feed water, but RO is not considered a stand-alone technology for pH reduction.

5.8.2 Summary Evaluation and Discussion for Each Water-Supply Well

The following table is a summary of the constituents identified in each water-well that could be targeted for water treatment. An evaluation for potential water treatment for each water-supply well is in **Appendix Q**. This evaluation only addresses the wells used for domestic purposes. The three study wells that are identified as stock or stock/irrigation wells are not included in this discussion.

Well ID	Ferrous Iron	pH	Turbidity	Iron	Manganese	Sodium	Chloride	Nitrate	Sulfate	TDS	Arsenic	Lithium	Thallium	Uranium and Gross Alpha	Radon-222	Radium, tot	Microorganisms	RO System in Place
PGDW05		X		X		X			X	X							X	
PGDW14			X			X			X	X			X	X	X		X	X
PGDW20		X				X			X	X							X	X
PGDW23		X				X			X	X					X		X	
PGDW30		X				X			X	X							X	
PGDW32		X				X			X	X					X		X	
PGDW33						X			X	X				X	X		X	
PGDW41 A						X	X	X	X	X	X	X	X	X	X		X	
PGDW41 B	X		X	X	X	X			X	X		X				X	X	
PGDW42	NA	NA	NA			X			X	NA		NA		NA	NA	NA	NA	

Note: Water from PGDW14 exceeds MCL for gross alpha but not uranium.

NA= not analyzed. Well PGDW42 was not included in the 2014 study, therefore available data are limited.

As each of the water-supply wells appears to have an issue with one or more microbiological constituents (coliform, iron bacteria, and/or sulfate bacteria), in-line chlorination would be a consideration for each of the wells if shock treatment has been or is tried and found not to be sufficiently effective.

In addition, a common issue to all the water-supply wells is elevated sodium, which can be treated by IX or RO. The drawback for treating with IX is the strong acid necessary to regenerate the resin for sodium treatment and the drawback for RO being the relatively high water rejection (waste) rate.

5.9 Data Limitations/Evaluation

5.9.1 Evaluation of Data from MW01 and MW02 Installed by the US EPA

In June 2010, the US EPA installed two deep monitoring wells, MW01 and MW02, intending to differentiate deep versus shallow groundwater quality. The primary conclusion from the US EPA draft report that constituents associated with hydraulic fracturing have impacted the drinking water aquifer was based on water-quality data collected from the two deep monitoring wells, including the presence of high pH, elevated levels of chloride, potassium, and petroleum hydrocarbons, and other organic compounds that may be used in hydraulic fracturing.

Some reviewers of the draft report identified concerns with the drilling, construction, development, and sampling of the two deep monitoring wells, and in the interpretation or representations of the resultant groundwater quality results (Sterrett, 2012; Mullen, 2012; SSPA, 2012; API, 2013).

Based on the unresolved questions regarding the representativeness of the data collected from the two deep monitoring wells, the data are not further discussed or used in this study.

5.9.2 Other Potential Sources of Petroleum Hydrocarbons

The potential for the numerous drilling and production pits to act as contamination sources was evaluated in the WOGCC Pit Report as well as summarized in this report. Other potential oil and gas exploration and production related sources such as drill cuttings disposal sites represent a potential source of petroleum constituents and dissolved salts that has not been evaluated. Drill cuttings from pits that contained oil-based mud would be of particular concern. For example, one disposal site is reportedly located approximately 800 ft west-northwest of PGDW14, and received cuttings from gas well Government Tribal 33X-10 (**Table 9**).

Gas production facilities, such as condensate separators, dehydrators, gathering pipelines and associated above-ground storage tanks have also not been considered in this analysis. These facilities may represent potential source areas for petroleum constituents present in gas condensate and wastewater extracted from the gas stream.

5.9.3 Use of Water-Supply Wells in Hydrogeologic Investigations

As discussed previously, when interpreting the results of the groundwater samples from water-supply wells, consideration should be given to the differences between water-supply wells and monitoring wells. Water-supply wells typically have the following characteristics relative to monitoring wells: larger diameter, different construction materials, much more frequent pumping (with accompanying changes in hydraulic head and groundwater chemical characteristics), and screened or perforated intervals which may intersect multiple separate permeable intervals. Other potential effects discussed in previous sections include the presence of pressure tanks between the well and some of the sampling locations, drawdown of the water level to near the pump

intake in some instances, and finally the well construction itself, with further uncertainty arising from the lack of detailed construction information for some of the water-supply well.

5.9.4 Analytical Detection Limits

Analytical methods utilizing GC/MS may include extensive lists of target compounds. Such methods include VOCs by EPA Method SW8260B and SVOCs by EPA Method SW8270C. Because of the extensive target compound list, the MDL for some of the analytes was greater than the corresponding drinking water standard or comparison values (**Table 29**). In the table, the drinking water standards or comparison values were applied in the order listed: first use EPA MCL, if none then use WY Class I Domestic, then if none use EPA DWEL, then if none use WY DWEL. The table also lists the number of detections in the groundwater samples (all zero) and describes sources of each chemical as described in ATSDR (2015), Budavari (1996), and NIH (2015).

For the two VOCs listed in **Table 29**, the MDL was greater than the EPA MCL for one sample for 1,2-dibromo-3-chloropropane and was twice the MCL for 1,2-dibromoethane (aka ethylene dibromide or EDB) for all samples. Both chemicals were formerly used as pesticides, and EDB was also used as an additive in leaded gasoline.

The SVOCs listed in **Table 29** are listed in three groups:

- Pesticides, wood treatments, and commercial products (3 chemicals)
- Polynuclear aromatic hydrocarbons (PAHs, 6 chemicals)
- Industrial chemicals used in manufacturing or a manufacturing by-product (3 chemicals)

These SVOCs are not generally associated with oil and gas production or hydraulic fracturing operations, with the exception that PAHs may be present in petroleum asphalt. For the chemicals listed in the first group (hexachlorobenzene, pentachlorophenol, and phenol), the MDLs were between 0.77 and 2.1 times the corresponding drinking water standards.

6. CONCLUSIONS AND CONSIDERATIONS FOR ADDITIONAL WORK

6.1 Conclusions

The Pavillion Gas Field is a conventional reservoir with unique characteristics. This includes the presence of non-commercial quantities of gas in relatively shallow zones, the absence of a regional confining layer, a spatial density of gas wells at 40-acre spacing, and vertical gas wells with relatively shallow uppermost perforations. The Pavillion Gas Field is different than gas fields recently associated with hydraulic fracturing in other areas, in that the gas is sourced from permeable sand reservoirs using standard vertical wells, and not sourced from less permeable shale using horizontally-drilled wells.

Gas in the Wind River Formation appears to have originated mainly from upward migration from deeper gas-bearing zones, most likely due to the absence of a regional confining layer. The shallow Wind River Formation gas and deeper Fort Union Formation gas are very similar chemically and isotopically and are thermogenic in origin.

Evidence suggests that upward gas seepage (or gas charging of shallow sands) was happening naturally before gas well development.

It is unlikely that hydraulic fracturing fluids have risen to shallower depths intercepted by water-supply wells. Evidence does not indicate that hydraulic fracturing fluids have risen to shallow depths intersected by water-supply wells. The likelihood that the hydraulic fracture well stimulation treatments (i.e. often less than 200 barrels) employed in the Pavillion Gas Field have led to fluids interacting with shallow groundwater (i.e. water-supply well depths) is negligible.

Potential movement of groundwater and/or gas from intermediate pressurized zones into shallower permeable zones intercepted by water-supply wells could possibly have caused changes in water quality. Potential communication of groundwater, gas, or both exists between shallow water-bearing zones and intermediate zones that were both intercepted by gas wells. The most likely conditions for vertical seepage to occur include: 1) a gas well with an annular space without cement adjacent to production casing, 2) a relatively shallow surface casing in the same gas well, 3) an intermediate permeable zone pressurized by gas, 4) one or more permeable groundwater zones that intersects the gas well below the surface casing shoe. It should be noted that existing WOGCC rules were followed for all gas wells at the time of their construction.

Some gas wells are experiencing slow gas seepage. Bradenhead gas observed in gas wells is more likely to have originated from intermediate zones containing non-commercial quantities of gas. Sustained Bradenhead pressure in a gas well would indicate the likelihood of movement of groundwater and/or gas is greater at that well.

Gas in samples obtained from water-supply wells is thermogenic gas that shows signs of alteration by biodegradation and migration. Chemical and isotopic data do not suggest a shallow biogenic source.

The relative contribution of potential gas seepage along gas wells versus natural upward migration of gas is undefined and would be very difficult to quantify.

Characteristics of groundwater in the water-supply wells included in the study are consistent with groundwater quality for the Wind River Formation within the Wind River Basin. Concentrations of sodium, sulfate, and TDS exceed drinking water standards in most water-supply wells within the Wind River Basin, including the water-supply wells in the study.

Limited baseline water quality data, including methane, that predates development of the Pavillion Gas Field hinders reaching firm conclusions on causes and effects of reported water quality changes.

Exceedances of water quality standards in most cases are for naturally occurring dissolved salts, metals, and radionuclides. Exceedances of water quality standards for synthetic organic compounds are limited to one reported pesticide concentration, plus a phthalate ester which is a common laboratory contaminant and a constituent of plastics used in water-supply systems.

All other organic chemicals reported in groundwater samples are at concentrations less than drinking water standards or comparison values and may originate from a multitude of possible sources. For example, petroleum constituents (isopropyl benzene and naphthalene) may be attributable to surface spills from fueling vehicles and/or releases from gas well pits. Some organic chemicals reported in the groundwater samples (e.g. acetone, methylene chloride, 2-propanol) are likely laboratory artifacts. Reported GRO and DRO concentrations may represent a variety of organic compounds, possibly including naturally-occurring organic compounds and/or byproducts of bacterial growth.

Geochemical changes associated with the biodegradation of dissolved organic compounds likely have produced constituents associated with poor water palatability, and appear to be linked to declining well yields. The bacteria include iron-related and sulfate-reducing bacteria. Biodegradation of dissolved organic constituents through sulfate reduction produces sulfides. Also, biodegradation will create reduced groundwater conditions, which will increase the solubility of naturally occurring constituents, including metals, such as arsenic, iron, and manganese. Many of the water-supply wells included in the study show the effects of iron-related and sulfate-reducing bacteria, including chemically reduced groundwater and other geochemical changes.

Existing data from investigations at former pit locations requires more detailed review to assess the potential to impact groundwater quality in water-supply wells. The analysis included in the Pit Review Report was not detailed enough to assess whether the site investigations and/or remediation were sufficient to protect groundwater quality in water-supply wells located within 1,420 ft of the pit locations. Additional assessment would benefit from using existing data (e.g.

groundwater results from VRP investigations) augmented with published guidance or studies from other areas to further address this question.

6.2 Considerations for Additional Work

Identification of groundwater constituents that cause palatability issues. Additional sampling is recommended for constituents associated with palatability issues (e.g. organosulfides, sulfides analysis in field) or other geochemical/biomarkers for iron and sulfur bacteria such as quantitative polymerase chain reaction (qPCR) quantification of bacterial populations in groundwater. This additional sampling would help identify the origin of specific bacteria and assist in designing a treatment method for the well water. The additional targeted sampling should be complemented with limited analyses for general water quality parameters (e.g. major cations/anions and TDS) to assess comparability of the groundwater samples to earlier sample data. The additional analyses could include:

- Iron-related bacteria by qPCR (proprietary method)
- Sulfate reducing bacteria by qPCR (proprietary method)
- Organosulfides (e.g. thiols, thioethers, disulfides) by GC/MS (e.g. EPA SW8270D-modified; lab-specific)
- Sulfides in field by Hach kit using EPA SW8131
- Major cations, anions, and TDS as in the 2014 sampling (SW6010B, EPA 300.0, SM 2320B, and SM2540C).

Assessment of the potential for gas seepage along gas wells versus naturally occurring upward seepage of gas, as well as evaluating if conditions are present to allow the potential movement of liquid and/or gas from intermediate zones pressurized by gas into shallower permeable zones. Field activities may be conducted near gas wells to observe potential vegetative stress and gas bubbling when the surface is wet. This information can be used to assess whether gas seepage along gas wells is occurring or has occurred. Soil gas sampling from spatially distributed locations is preferred to quantitatively assess the upward seepage of gas as a function of distance from gas wells, so that the relative contribution from gas wells versus natural occurrence may be estimated.

Additionally, existing data, including well logs for a) potential intermediate to shallow gas zones, b) potential shallow permeable groundwater zones, c) casing cementing conditions, and d) information on Bradenhead pressure should be reviewed and evaluated. This would allow the potential migration conditions to be classified as more likely or less likely. Further investigation may then be directed at the most likely conditions identified, and may include installing multiple monitoring wells completed in different permeable zones, and collecting and analyzing data from the monitoring wells and water-supply wells completed at similar depths.

Evaluation of whether surface pits contribute to water-quality issues in water-supply wells. Because the pits that have been identified as a potential risk to groundwater have already been enrolled in, and are being investigated through, the WDEQ VRP, it is recommended that this corrective action process be allowed to be completed using that program. Additionally, the WOGCC Pit Report recommended further investigation of numerous closed pits.

Once the VRP investigations and WOGCC recommended field work are complete, a detailed review of available data for existing and closed pits should be performed. This evaluation should be augmented with studies from other oil and gas pit study areas and related published guidance. Investigation and evaluation is needed for the LSND mud-type and the KCl polymer-type pits, as they contained different types of constituents than some of the invert mud-type pits that the VRP sites and WOGCC-recommended investigations are addressing. Depending on the outcome of this evaluation, it may then be beneficial to conduct an expanded investigation (e.g., additional monitoring wells at multiple depths and analysis of more constituents) at selected sites of different characteristics to demonstrate whether surface pits contribute to water-quality issues in water-supply wells.

Consideration of other potential sources of petroleum hydrocarbons such as drill cuttings disposal sites and gas production and gathering facilities. At a minimum, an inventory of these potential sources, mapping of their locations relative to water-supply wells, and the history of activities at these sources should be developed. Preliminary field investigations, if warranted, including soil and groundwater sampling could be conducted at select potential source locations, so that the necessity of further investigation may be determined.

Organic chemical detection limits. As part of the additional sampling recommended above, analyze samples for VOCs and SVOCs to achieve lower MDLs for the five specific chemicals discussed above (1,2-dibromo-3-chloropropane, EDB, hexachlorobenzene, pentachlorophenol, and phenol) and other chemicals listed on **Table 29** as necessary. To achieve lower MDLs for these chemicals, use methods such as EPA 524.2 for VOCs and EPA SW8270 with selective ion monitoring targeted at the three SVOCs.

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