Normally Pressured Lance Natural Gas Development Project

Final Environmental Impact Statement

Appendix K

Water Resource Support Appendix

NORMALLY PRESSURED LANCE (NPL)

NATURAL GAS DEVELOPMENT PROJECT

WATER RESOURCE SUPPORT APPENDIX

U.S. Department of the Interior
Bureau of Land Management

BLM Pinedale Field Office
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Pinedale, Wyoming 82941

The BLM manages more land – 253 million acres – than any other Federal agency. This land, known as the National System of Public Lands, is primarily located in 12 Western States, including Alaska. The Bureau, with a budget of about $1 billion, also administers 700 million acres of sub-surface mineral estate throughout the nation. The BLM's multiple-use mission is to sustain the health and productivity of the public lands for the use and enjoyment of present and future generations. The Bureau accomplishes this by managing such activities as outdoor recreation, livestock grazing, mineral development, and energy production, and by conserving natural, historical, cultural, and other resources on public lands.

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ACRONYMS AND ABBREVIATIONS

°C	degrees Celsius
µS/cm	micro Siemens per centimeter
AGWA	Automated Geospatial Watershed Assessment
bgs	below ground surface
BLM	Bureau of Land Management
BTEX	Benzene, toluene, ethylbenzene, xylenes
EIS	Environmental Impact Statement
Encana	Oil & Gas (USA) Inc.
EPA	U.S. Environmental Protection Agency
ft. bgs	feet below ground surface
GC/MS	Gas Chromatography/Mass Spectrometry
GGRB	Greater Green River Basin
GPM	Gallons per minute
GRB	Green River Basin
HSU	hydrostratigraphic units
HUC	Hydrologic Unit Code
JIDPA	Jonah Infill Drilling Project Area
MCL	maximum contaminant level
mg/L	milligrams per liter
MSL	mean sea level
NPL	Normally Pressured Lance
PAPA	Pinedale Anticline Project Area
PFC	Proper Functioning Condition
PFO	Pinedale Field Office
RGF	Regional Gathering Facility
ROD	Record of Decision
RSFO	Rock Springs Field Office
SU	standard unit
SVOC	semi-volatile organic compound
TDS	total dissolved solids
TPH-DRO	Total petroleum hydrocarbons – diesel range organics
TPH-GRO	Total petroleum hydrocarbons – gasoline range organics
USDW	Underground source of drinking water
USGS	United States Geological Survey
VOC	volatile organic compound
WDEQ	Wyoming Department of Environmental Quality
WOGCC	Wyoming Oil and Gas Conservation Commission
WSGS	Wyoming State Geological Survey

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1.0 INTRODUCTION

The purpose of this document is to present a targeted analysis of key technical issues associated with water resources to support the description of the affected environment (Chapter 3) and environmental consequences (Chapter 4) for water resources in the Normally Pressured Lance (NPL) Natural Gas Development Project Environmental Impact Statement (EIS). This targeted technical analysis specifically addresses the following NPL Project activities that could result in impacts to water resources:

- Disturbance of surface conditions from construction activities and infrastructure that could affect surface water runoff, infiltration rates, sedimentation, and surface and groundwater quality;
- Removal of groundwater from the top 1,000 feet of the Wasatch Formation, and the potential for depletion of groundwater resources; intrusion of lower quality water; and lowering of the potentiometric surface;
- Injection of formation fluids into the Fort Union Aquifer (4,000 to 8,000 feet below ground surface [bgs]), and the potential for impacts to water quality in shallower aquifers; and
- Loss of drilling fluids and completion fluids into water zones during drilling and well completion operations.

The analysis area for water resources described in this appendix and in the NPL Project EIS includes the following:

- The entire extent of the 15 Hydrologic Unit Code (HUC)-12 watersheds that intersect the Project Area, including the surface runoff and channel discharge points identified in Appendix J (*AGWA Technical Report*);
- Aquifers underlying the Project Area and potential migration/transport pathways outside the Project Area; and
- Groundwater at the supply wells that will be used for the NPL Project that are located outside of and within the Project Area, including the area of influence of these wells.

2.0 INFORMATION SOURCES

The Project Area is located in the northern portion of the Green River Basin (GRB), within the Upper Green River and Big Sandy River subbasins in Wyoming. Because of the limited extent of development in the NPL Project Area, limited data have been collected from within the NPL Project Area on geology, water resources, water quality, and hydrogeology.

To support timely completion of the NPL Project EIS, the water resources analysis utilizes readily available existing information from the adjacent Jonah Infill Drilling Project Area (JIDPA) and the Pinedale Anticline Project Area (PAPA), as well as NPL Project Area-specific studies conducted to date, as described below. The project proponent has initiated a voluntary water quality sampling and analysis program to document current water quality in selected wells and springs in the NPL and adjacent areas. The sampling program is ongoing, and data from the program have been provided to the BLM for use in developing the NPL Project EIS. Due to relatively similar geological conditions, it is assumed that conditions in the NPL Project Area would be similar to those in the JIDPA. An NPL Groundwater Monitoring Program will be implemented by the project proponent prior to development to provide additional information on groundwater conditions and to monitor potential impacts resulting from the project. The NPL Groundwater Monitoring Program will be consistent with WOGCC regulations and is different than operator's sampling and analysis program described and referenced in this appendix. The primary information sources used for the NPL Project EIS are described below. Because there has been limited project-area specific data collection, the sources used represent the best available information to evaluate water resources. Limitations of these readily available existing data are described below.

The Groundwater Flow Model and Hydrogeologic Impact Assessment, Jonah Infill Drilling Project (HydroGeo 2004) report summarizes results of a numerical model designed to simulate the regional effect on water resources from pumping groundwater from the Green River/Wasatch aquifer system. The model was based on simulating pumping water supply wells that would also be used to supply groundwater for the NPL Project. The results of this model describe the drawdown of groundwater that would result from removing water for drilling wells for the Jonah Project and approximates the time it would take for groundwater levels to return to normal conditions. The report describing the methods and model results is included as Attachment A (*Groundwater Flow Model and Hydrogeologic Impact Assessment)*. The model domain includes all of the NPL Project Area, with all pumping wells located within the JIDPA. The time frame for the most intense development systems for the JIDPA is 10 years, and intensive water use for the JIDPA is expected to decrease as development for the NPL Project increases.

Groundwater Well Inventory and Assessment in the Area of the Proposed Normally Pressured Lance Natural Gas Development Project, Green River Basin, Wyoming, 2012 (USGS 2013). The United States Geological Survey (USGS), in cooperation with the Bureau of Land Management (BLM), inventoried and assessed existing water wells in and around the NPL Project Area for inclusion in a possible groundwater monitoring network for the NPL Project. The study area encompassed all of the NPL Project Area and extended beyond the analysis area boundary. No water level or water quality samples were collected as part of this investigation. A total of 376 wells were identified in the study area based on available records. Of these, 141 well records contained sufficient information to evaluate the wells. Efforts were made to locate these 141 wells, but only 121 wells were found. Of the 121 wells, 92 met established monitoring well criteria and could potentially be used for the groundwater monitoring program; however, water level measurements could be made in only 79 of these wells. In this report, USGS summarizes the results of its record search and field inspection of these 79 wells. Wells are typically screened across a discrete water-bearing zone or aquifer. USGS reports that four of the 79 wells are screened in the shallow alluvial aquifer, 14 are screened in the Laney Member of the Green River Formation, 49 are screened in the Farson Sandstone Member of the Green River Formation, and 12 spanned three different units of the Wasatch Formation.

Normally Pressured Lance (NPL) Natural Gas Development Project: Modeling the Effects of Surface Disturbance Using the Automated Geospatial Watershed Assessment (AGWA) Tool – Technical Report (BLM 2013a). Results of the AGWA modeling identify areas within the NPL Project Area that would be most susceptible to increased erosion, surface runoff, and sediment transport under the Proposed Project. The model was also used to estimate changes in surface runoff and channel discharge that would result from surface disturbance and infrastructure associated with the NPL Project. Based on this analysis, areas were identified where runoff/erosion monitoring and/or more extensive mitigation activities should be focused, or areas where development should be minimized or avoided. The AGWA model domain includes the full extent of watersheds that intersect the NPL Project Area. The AGWA Technical Report is included in the NPL Project EIS as Appendix J (*AGWA Technical Report*).

Final Hydrogeologic Conceptual Model for the Pinedale Anticline Project Area (PAPA), Sublette County, Wyoming (Geomatrix 2008). Final Technical Report: Hydrogeologic Data Gaps Investigation Interim Plan, PAPA (AMEC 2012), and Numerical Groundwater Modeling Report (AMEC 2013a). These documents present the conceptual model at the PAPA including an overview of water resources; recharge, discharge, and flows; and a description of discrete hydrostratigraphic units within the 308-square-mile PAPA, which lies outside of the NPL Project analysis area. The PAPA differs from the NPL Project Area because it has been in production for many years; it contains surface water resources that interact with the upper aquifer system; and in general, the PAPA is different because it contains a higher percent of sand layers than the NPL due to its proximity to the source area. Hydraulic measurements reflect the best information available at this time, and due to similar geologic conditions, some of the information from this conceptual model, such as general hydrologic characteristics, is relevant to the NPL Project Area. The PAPA is formed by a structural anticline formed by a thrust fault with the northeastern side thrusting upward, whereas the NPL Project Area is a broader basin-centered gas accumulation with little confirmed faulting/fracturing. Surface waters, including the New Fork River, are present within the PAPA. The NPL Project Area has no permanent surface waters. The main hydrostratigraphic units (HSUs) described for the PAPA, as summarized below, are based on the site-specific stratigraphy within the PAPA assessment area. Over time the studies have led to an improved understanding of the hydrostratigraphy, and the delineation of HSUs has changed since 2008. The most recent understanding of the hydrostratigraphic units are described below. There has been no attempt to formally correlate or evaluate these as distinct units in the NPL Project Area.

- **Alluvial HSU**: Groundwater contained in sand and gravel deposits adjacent to the streams and rivers are classified as the Alluvial HSU. The deposits are generally no more than approximately 30 feet thick and are partially saturated. This HSU is hydraulically connected to the underlying Wasatch Formation, as well as to subjacent streams and rivers. Six domestic wells draw from this aquifer in the PAPA. A similar unit is present in the NPL Project Area, but due to the limited areal extent and distance between the NPL and PAPA, the units are unlikely to have a hydraulic connection.
- **Wasatch HSU**: Permeable sandstone units or lenses within the thick shale/siltstone units containing groundwater are described as the Wasatch HSU. Continuous water-bearing sandstone beds have not been documented over large areas because of the fluvial channel architecture of the Wasatch Formation. Groundwater in the Wasatch HSU in the PAPA is found under confined (artesian), semi-confined, and unconfined conditions. Sandstone lenses are not

continuously saturated, and in some areas perched groundwater may discharge locally to springs. The PAPA model does not provide a total depth or thickness of the HSU, but notes that the maximum depth of industrial wells within the Wasatch HSU is 1,210 feet. The stratigraphy and groundwater conditions of the Wasatch HSU at the PAPA are similar to those at the NPL Project Area. The Wasatch HSU is equivalent to the Wasatch Aquifer, as used in the NPL Project EIS and in this appendix. Within the PAPA, the Wasatch HSU has a greater net thickness of sand layers (Bartos and Hallberg 2010) and occurs at ground surface. In the southern part of the NPL Project Area, the Wasatch Aquifer underlies the Laney Aquifer.

- **Fort Union HSU:** Found in both the PAPA and the NPL Project Area; the Fort Union HSU is the target zone for formation fluids injection in both fields. The Fort Union Aquifer was not part of the PAPA numerical model.

The PAPA reports cited above do not include analysis or information relating to faulting or fracturing that could result in vertical migration pathways.

Evaluation of Potential Sources of Low Level Petroleum Hydrocarbon Compounds Detected in Groundwater, Interim Plan, Pinedale Anticline Project Area Record of Decision (ROD), Sublette County, Wyoming (AMEC 2013b). This report evaluates potential sources of low level hydrocarbon contamination identified in several water supply wells within the PAPA. This report builds upon previously completed aquifer characterization and numerical modeling studies in the PAPA and includes extensive sampling and analysis of water supply wells and potential source materials including flowback fluid, oil-based drilling mud, condensate, produced water, light nonaqueous-phase liquid, water supply well pump materials, and carbonaceous shale.

The investigation identified no evidence of widespread impacts to groundwater in the PAPA due to natural gas exploration and production activities. It identified the following known or potential sources of low levels of petroleum hydrocarbons in water wells:

- Upward seepage by natural processes of natural gas from deep, underlying gas reservoirs over time into overlying geologic layers where groundwater occurs;
- Organic constituents introduced into water wells during drilling, installation, and operation of natural gas wells; and
- Naturally occurring organic matter in groundwater or associated with particles suspended in water wells during sample collection.

Water supply wells to be used for the NPL Project may have been constructed or operated under similar conditions as those at the PAPA, and the potential for petroleum hydrocarbon contamination is possible by the same mechanisms.

NPL Project Sampling and Analysis Annual Reports (Trihydro 2011, 2013, 2014a, 2014b).[1] The operator for the NPL Project retained Trihydro Corporation (Trihydro) to conduct annual, project-specific water sampling and laboratory analysis from existing wells and springs within and adjacent to the NPL Project Area in 2011, 2012, 2013, and 2014 with on-going additional sampling and analysis. The purpose of the sampling and analysis is to document the water quality in the existing wells and springs prior to development of natural gas resources in the NPL Project Area and subsequently to provide indication of any changes to the quality of the water after development has begun. Although these are tests of water

[1] Note that the dates referenced are the publication dates of the sampling and analysis reports. The actual sampling and analysis was conducted annually in 2011, 2012, 2013 and 2014.

quality in existing wells and springs, it is important to note that these are not monitoring wells and results may not reflect actual groundwater conditions. These annual sampling and analysis activities will be on-going throughout the project, with potential changes to locations of sampled wells in response to the NPL Project Record of Decision (ROD), pending groundwater monitoring plans for the NPL Project and other factors. The operator, in coordination with the BLM and other entities will develop and implement a groundwater monitoring program prior to initiating development to provide additional information on groundwater conditions.

Water samples were analyzed for general water quality parameters, total metals, and organic contaminants including volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), dissolved gases, alcohols, glycols, radiochemicals, total petroleum hydrocarbons, and aldehydes. Results indicate overall good groundwater quality and are further discussed within this report.

When available, information on well installation and boring logs was collected and reviewed to help understand the stratigraphy and the aquifer in which the wells were screened. An initial groundwater characterization was performed by Trihydro (2013) and determined that of the 26 wells that were located, four were determined to be screened in the alluvial aquifer based primarily on their shallow depths and unconfined conditions. Consistent with the very limited occurrence of the alluvial aquifer in the NPL Project Area, only one of the alluvial wells is located within the NPL Project Area and the remaining three shallow wells are located outside the Project Area. Measured depths of the remaining 22 wells were 210 to 1,573 feet bgs, indicating that they draw water from the shallow zones of the Wasatch Formation, which is the primary source of groundwater in the GRB. In 2014 Trihydro conducted a second analysis of available wells in the NPL area to incorporate the requirements of the new WOGCC rule for baseline water sampling (Trihydro 2014c). Within one mile of the NPL Project Area Boundary, 52 wells with SEO permits were recognized as complete or have been field verified. Additionally, three water sources were field verified by Trihydro and/or the USGS that do not have SEO permits, for a total of 55 identified water sources. Twelve of these water wells have not been field verified by Trihydro.

Annual Water Quality and Well Depletion Reports for JIDPA (AECOM 2008, 2009, 2011, 2014; AMEC 2010, 2013, 2014; BLM 2006a; BP 2004a, 2004b, 2009, 2010, 2011, 2012; Encana 2009, 2010, 2014; Linn Energy 2013, 2014). Under the 2006 ROD for the JIDPA, operators are required to submit annual reports to the BLM of the amount of water used for each water supply well at the JIDPA. Additionally, the operators are required to sample the active water wells annually and provide water quality information to the BLM. Water quality data also include the analysis of one well (Corona 2-14) currently not in use due to detection of petroleum hydrocarbons. Since 2006 several different operators have provided this information to the BLM as letter reports, and the BLM has made those data available for the NPL Project EIS and this analysis. Because the same water supply wells currently used for the JIDPA are anticipated to be used for the NPL Project, the data provided from these wells are directly applicable to the water quality and depletion analysis for the NPL Project presented in the NPL Project EIS and this appendix.

3.0 PHYSICAL SETTING

The NPL Project Area is located primarily on BLM-administered lands managed by the BLM Pinedale Field Office (PFO) and Rock Springs Field Office (RSFO) within Townships 27 through 29 North, Ranges 107 through 110 West, 6th Principal Meridian, in Sublette County, Wyoming (Figure K-1). The JIDPA is directly adjacent to the northeastern portion of the NPL Project Area. The PAPA is north of the JIDPA, in the northern portion of the GRB. The locations of the water supply wells within the JIDPA, which would supply water for NPL Project development, are depicted in Figure K-2.

The analysis area is characterized by low rolling hills interspersed with buttes, rock outcrops, large draws, and deep canyons (Clarey and Thompson 2010). The NPL Project Area consists primarily of shrub-steppe habitat dominated by Wyoming big sagebrush and grasses. There is a surface water drainage divide within the NPL Project Area between the Green River, approximately five to ten miles to the west, and the Big Sandy River (a tributary of the Green River), approximately five miles to the east (BLM 2013a).

Primary land uses in the general vicinity of the Project Area include livestock grazing, recreation, wildlife habitat, agriculture, and, increasingly, oil and gas development. Since 1992, development of the extensive oil and gas fields adjacent to the Project Area—including the PAPA to the north; the Riley Ridge and Big Piney/LaBarge Coordinated Activity Plan to the west; and the JIDPA to the immediate northeast—has greatly increased the level of human activity in the area and decreased the amount of land available for other uses. Prior to this surge in mineral exploration, the lands were primarily used for livestock grazing, with some areas frequented by recreationists searching for petrified wood or hunting for antelope and Sage-Grouse.

Thus far, the development of oil and gas resources within the Project Area has proceeded at a far slower pace than in surrounding fields. As of 2015, 116 wells have been drilled in the Project Area (WOGCC 2015), including:

- 55 producing natural gas wells;
- 19 dry/junked/abandoned wells;
- 1 Class II underground injection well (deep disposal of formation fluids);
- 10 water supply wells for oil and gas operations (drilling and completion operations, road construction, maintenance, dust control and reclamation) including 4 water supply wells for drilling in the JIDPA, and 1 water supply well for the Jonah workforce facility; and
- 31 existing stock water wells.

Figure K-2 in the NPL Project EIS identifies the location of the water supply wells and stock wells in the NPL Project Area. Attachment B (*Water Supply Wells in and around the NPL Project* Area) provides a description of the water supply wells in and around the NPL Project Area.

3.1 Climate

The NPL Project Area lies in a semi-arid, cold desert climate and is dotted with ephemeral washes and playas (Trihydro 2011). Precipitation is representative of a high desert region, and the area generally receives between approximately 7 and 11 inches of precipitation annually (Table K-1). Monthly precipitation ranges from around 0.2 to 1.7 inches. The highest precipitation rates occur in May through September, although average amounts of rainfall are generally very low and consistent throughout the year. Between 1999 and 2007, the GRB experienced an overall decrease in average annual precipitation (Wyoming State Geological Survey (WSGS) 2010).

Precipitation throughout the GRB is greatly influenced by topography, with higher amounts of rain and snowfall in mountainous areas surrounding the basin. The majority of water in the Project Area comes from precipitation and snowmelt from the mountains. The highest rates of runoff are anticipated in the spring, with little to no flow in the late summer season, and some flow beginning during the winter when evaporation rates are reduced with the cooler weather (BLM 2013a). Due to the arid climate, evaporation potential is approximately four times higher than annual precipitation (Geomatrix 2008). Given the low precipitation and high evaporation rates, little water is available for surface water runoff or infiltration through soils for groundwater recharge. Most groundwater recharge occurs through surface infiltration at the base of mountains along the perimeter of the basin.

Table K-1. Average Monthly Precipitation for Towns near the NPL Project Area

	Average Monthly Precipitation (inches)												Average Annual Precipitation (inches)
	January	February	March	April	May	June	July	August	September	October	November	December	
Big Piney, WY	0.31	0.35	0.43	0.51	0.83	0.79	0.71	0.71	0.79	0.51	0.20	0.31	6.45
Pinedale, WY	0.59	0.59	0.75	0.94	1.69	1.22	1.02	1.02	1.30	0.83	0.71	0.71	11.37
Farson, WY	0.35	0.31	0.51	0.75	1.42	0.87	1.02	0.67	0.94	0.67	0.39	0.35	8.25

Sources: US Climate Data 2015a, 2015b, 2015c.

Figure K-1. Surface Water Features in the Analysis Area

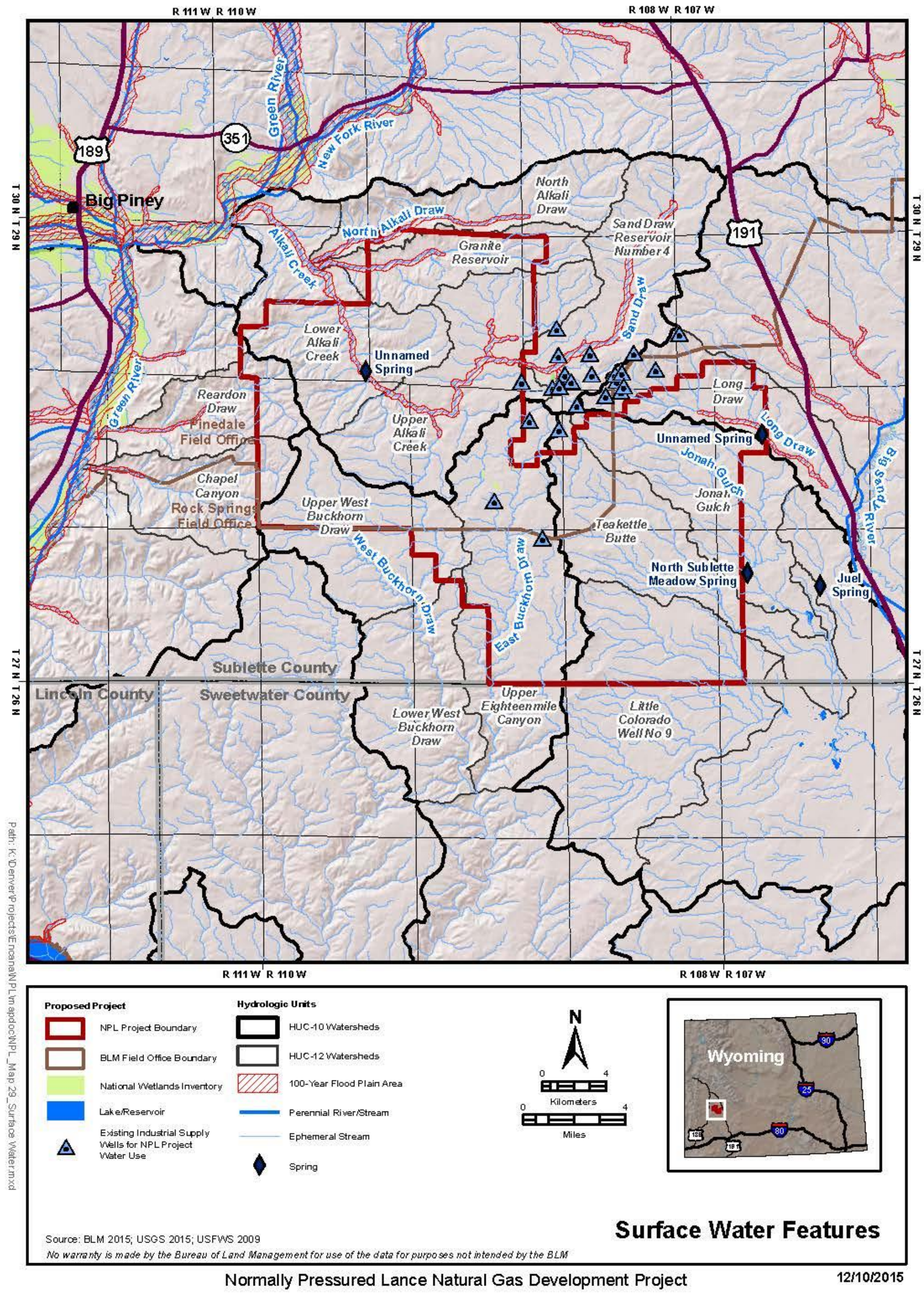
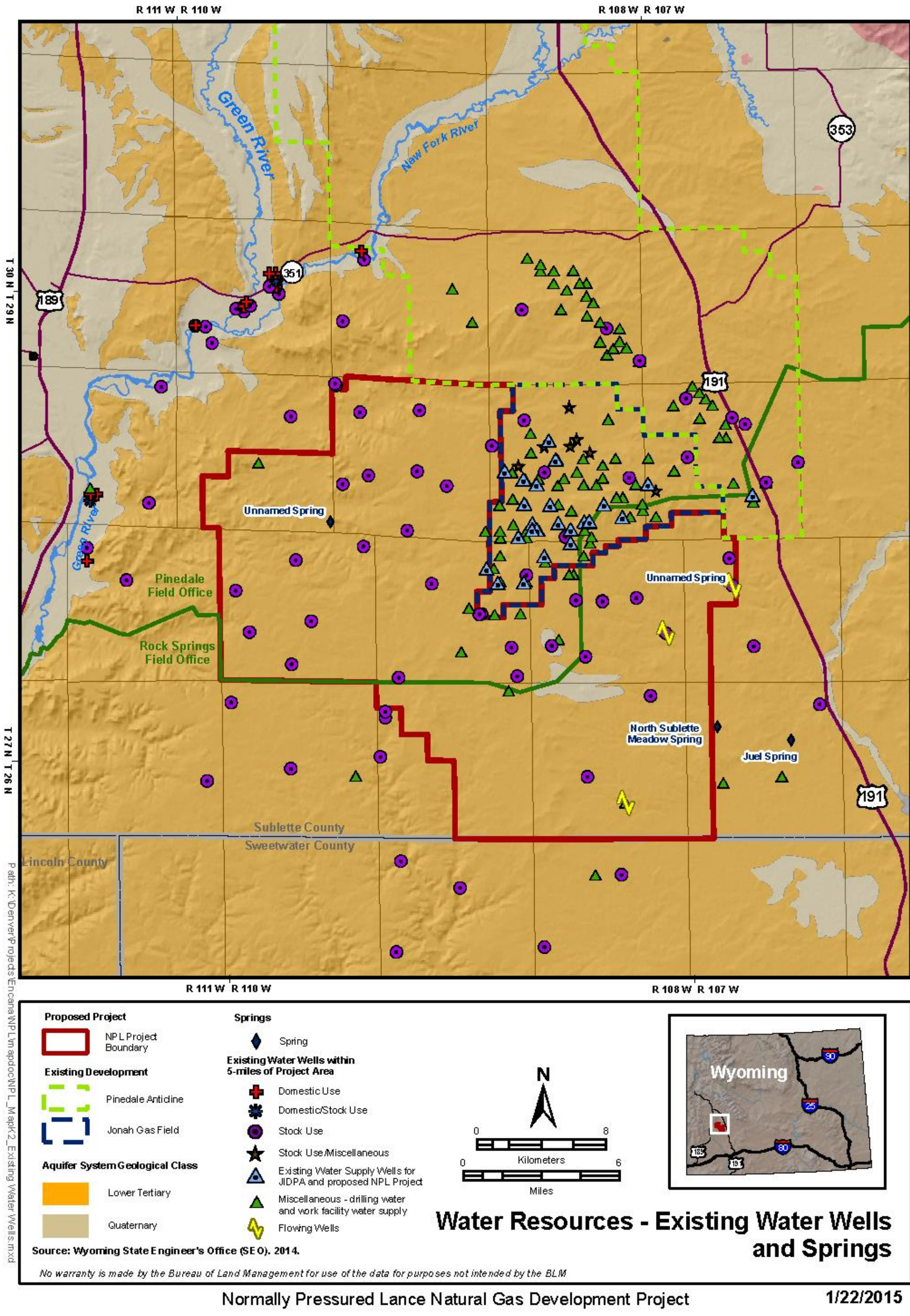


Figure K-2. Water Resources – Existing Water Wells and Springs



3.2 Geologic History and Structural Setting

The NPL Project Area is in the northwestern part of the geologic Greater Green River Basin (GGRB), in the Green River subbasin (referred to as the GRB or structural GRB). The geologic structural features that created the basins were formed beginning in the Jurassic period, approximately 140 million years ago and continued forming through the early Tertiary period, approximately 50 million years ago (Montgomery and Robinson 1997). The GGRB is bounded by deep thrust faults that uplifted the Uinta Mountains to the south, the Wind River Mountains to the north/northeast, and the Wyoming Thrust Belt to the west of the NPL Project Area. The Rock Springs Uplift to the southeast of the NPL Project Area was also created during this period. Figure K-3 illustrates the location of the NPL Project Area in relation to the major structural features of the GGRB. Downwarping and erosion associated with these uplifts created the structural GRB, which filled with up to 32,000 feet of sediments (Law 1996). Within the NPL Project Area, the entire sequence of Tertiary- and Cretaceous-age rocks represent non-marine sediments primarily formed in lacustrine and fluvial depositional environments (Warner 2000).

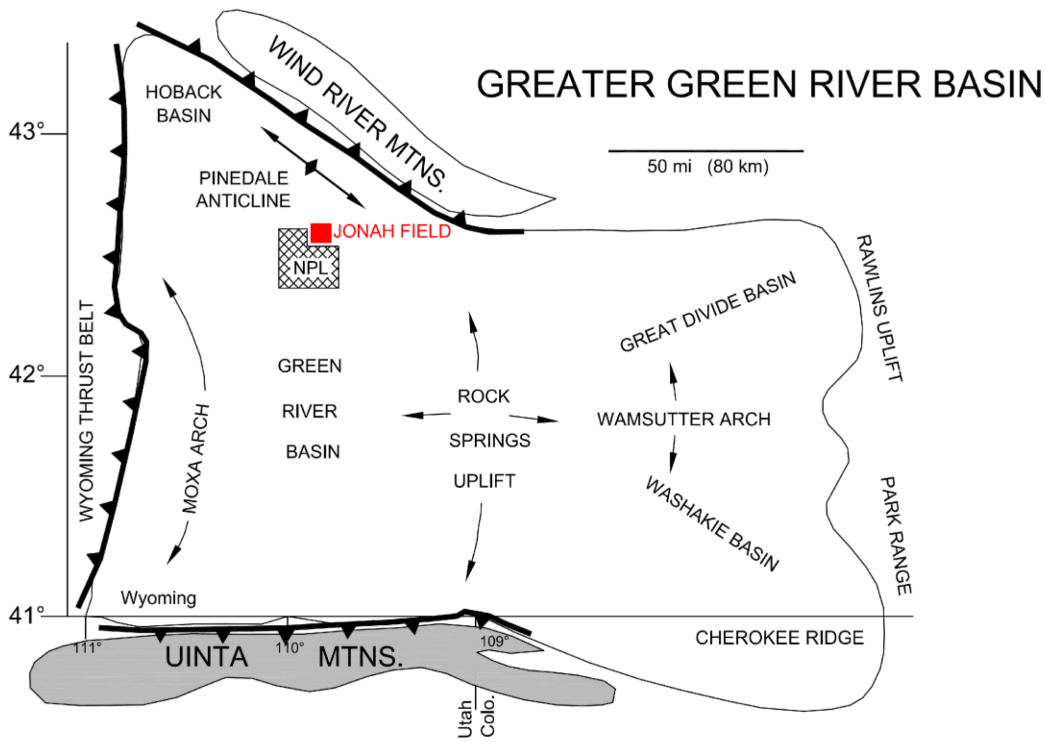
Smaller, regional structural features were formed with the major tectonic activities. These include the Pinedale Thrust and Anticline, the Moxa Arch-LaBarge Platform, and the bounding faults on the west and south of the JIDPA shown on Figure K-3. The Pinedale-Jonah area in the northern part of the GRB is structurally complex and contains a number of faults, folds, and associated fracture systems that created natural gas reservoirs. The Pinedale Anticline is 35 miles long and 6 miles wide and was formed as a result of uplift on the Wind River Thrust Fault (Law and Johnson 1989). It is oriented roughly parallel to the Wind River Thrust Fault. The southern end of the Pinedale Anticline is less than 10 miles to the northeast of the NPL Project Area. The PAPA lies within the Pinedale Anticline and produces gas from the Lance and other formations.

The Jonah Field, just northeast of the NPL Project Area and encompassing the JIDPA, is an over-pressured, fault-bounded, structurally trapped, basin-centered gas accumulation zone (Siguaw and Friend 2004). The faults that bound the Jonah Field are dominated by lateral movement (wrench faults) with little to no vertical movement. The faults have complex geometries with numerous splays and result in faulted blocks that create compartments of gas production in the Jonah Field (Warner 2000). Some of the faults within the Jonah Field have been interpreted to extend from the Precambrian basement upward into the Fort Union Formation (Warner 2000) and possibly to the surface; however, surface expression of such faults has not been verified or mapped. Seismic surveys acquired by Cabot Oil and Gas in December 2001 revealed that the faults extend one to two miles south and west of the currently productive area of the Jonah Field (Siguaw and Friend 2004), and that a northwest/southeast-trending thrust fault may be present within the NPL Project Area in the central part of T28N R109W. Camp (2008) and Grid Petroleum (2010) reference a seismic survey conducted southeast of the Jonah Field that appears to include part of the NPL Project Area. The authors interpret the results to include several northeast/southwest-trending faults in the area. These authors and Shanley (2004, as cited in Grid Petroleum 2010) describe the bounding faults at the Jonah Field as "sealing faults," indicating they are not transmissive and do not allow upward fluid migration. Other than the seismic survey conducted by Cabot, which focused on the southern tip of the Jonah Field within the NPL Project Area, no publicly available structural data is available for the NPL Project Area.

Based on readily available existing information from nearby similar, well-studied geological features, it appears that the NPL Project Area may have similar structural features, including faults and fractures, but at a smaller scale than the features that created the Pinedale Anticline or Jonah Field. If present, the faults and fractures would likely have a low possibility for transmitting fluids from producing zones to the shallow aquifer due to the limited vertical extent and the sealing nature of the faults as demonstrated in the nearby Jonah field; however, the NPL Project Area has not been fully investigated.

Based on currently available information it is difficult to definitively determine whether these faults could provide for communication between gas or liquids between producing zones and shallower aquifers. Additional information on communication between faults will be added as new studies become available and the NPL Project groundwater monitoring program will consider and apply new studies and information regarding fluid migration along faults and fractures as it becomes available. The groundwater monitoring program to be implemented to monitor water quality conditions prior to and during oil and gas development for the NPL Project would be used to evaluate the potential for fluid migration along existing and newly identified faults and fractures.

Figure K-3. Major Structural Features of the Greater Green River Basin



Source: Figure adapted from Montgomery and Robinson 1997.

3.3 Geology and Stratigraphy

Geologic data from exploration and production wells were used to develop a cross section through the NPL Project Area and the JIDPA (Figure K-4). The cross-section shows the geologic layers and primary zones of interest for the NPL Project Area and extends from south of and outside of the NPL Project Area to just north of the JIDPA. The interpreted depth and thickness of the geologic units and anticipated formation fluids injection zones were provided by the operator and based on analyses of geophysical logs, driller's logs, and local knowledge (Phillips 2013b). Sufficient data were not available to construct an east-west cross-section through the NPL Project Area. The zones depicted on the cross-section are described below from the oldest (deepest) to the youngest (shallowest).

The cross-section (Figure K-4) illustrates the relationship between the three primary zones of interest, which are, from oldest to youngest (deepest to shallowest), the Lance, Fort Union, and Wasatch

Formations. The Laney Member of the Green River Formation is present at the surface in the southern part of the cross section within the NPL Project Area. It is approximately 200 feet thick at the southern end of the cross section (Bartos and Hallberg 2010) and pinches out approximately at the NPL – Jonah boundary. This is not shown on the cross-section because the well logs used to select the tops of the formations do not extend to the surface where the Laney Member is present, and the Laney is too thin to be depicted at the scale shown. The Laney Member is known to contain oil shales, which contain solid organic matter but no free oil.

The Lance Formation would be the targeted gas-producing zone for the NPL Project and is the lowermost geologic unit shown on Figure K-4. The top of the Lance Formation becomes deeper to the north, and the target gas-producing interval also thickens to the north. Within the NPL Project Area, the Lance Formation is approximately 2,500 feet thick (Warner 2000) and thins to the southwest, where it pinches out at approximately eight miles to the southwest of the NPL Project Area. In the JIDPA, the lowermost sandstone beds of the overlying Fort Union Formation are included in the Wyoming Oil and Gas Conservation Commission (WOGCC) definition of the Lance Pool (Warner 2000, WOGCC 2003), and several wells in the JIDPA have producing intervals in the basal Fort Union Formation.

The top of the Lance Formation is marked by an erosional surface and a change in the composition of sediments. The Fort Union Formation lies above the Lance Formation and is approximately 4,000 feet thick in the NPL Project Area. It is informally subdivided into the basal, lower, and upper zones based on the presence of widespread geologic markers. The lower two-thirds of the upper Fort Union Formation is dominated by mudstones (Encana 2011a), but contains highly permeable, abundant porous sandstones, which are currently used in the JIDPA for disposal of formation fluids (as shown by Encana well SOL 119-7 WDW on the right side of the cross-section). This same zone is proposed as the injection and disposal zone in the NPL Project Area. The well logs in the NPL Project Area show that the upper Fort Union Formation consists of a series of shales, silts, and sands with a composite thickness of approximately 1,000 feet. Individual sands are generally less than 30 feet thick and are separated by up to several hundred feet of fine-grained materials. Regionally, the Fort Union Formation thins to between 2,000 and 3,000 feet thick to the northeast and southwest (Martin 1996) and is exposed at the surface near the Rock Springs Uplift, approximately 50 miles to the southeast.

The uppermost zone shown on the cross-section in Figure K-4 is the Wasatch Formation, which is similar in composition to the underlying Fort Union Formation. The Wasatch and Fort Union Formations have been designated as a single aquifer unit by the USGS (Martin 1996) and Wyoming Water Development Commission (Clarey 2010) but are hydrologically described as separate zones within the aquifer. In this report and the associated Environmental Impact Assessment, the broader terminology of the Wasatch Aquifer and Fort Union Aquifers are used and reflect the Wasatch Aquifer and Fort Union Zone of the Wasatch-Fort Union Aquifer. No regional confining unit separates the formations, and Martin (1996) describes groundwater flow across the boundary of the two formations. However, the chemical and hydrologic properties of the two formations are quite different. The Wasatch Formation is exposed at the surface in the northern part of the NPL Project Area and is approximately 3,300 feet thick at the southern end of the cross-section, thickening to approximately 4,200 feet in the JIDPA. Further north, the Wasatch Formation thickens to more than 7,000 feet and contains more thick, permeable, and extensive sandstones (Martin 1996). In the PAPA, the Wasatch ranges from approximately 3,000 to 7,000 feet (AMEC 2013a; as cited in Chafin and Kimball 1992; Glover et al. 1998; Martin 1996; Roehler 1992; Welder 1968). The sandstone layers in the JIDPA at depths of less than 1,000 feet are the source of freshwater for drilling and completion operations, and these same zones are also proposed as freshwater source zones for the NPL Project.

Although there is no clear contact between the Wasatch and Fort Union, they are not one continuous formation. Instead, there is a gradational change in lithology from approximately 1,200 feet in the Wasatch through the base of the Fort Union. The chemical composition of the formation water in the two formations are also different. Groundwater in the upper 1,200 feet of the Wasatch is generally of sodium-carbonate-bicarbonate type with TDS concentrations ranging from approximately 200 to 1,800 mg/L in the PAPA (SCCD 2013) and 373 to 4,330 mg/L in the NPL (Trihydro, 2014b). Groundwater in the Wasatch transitions from fresh water in the upper 1,200 feet to high salinity (greater than 40,000 mg/L) in the upper Fort Union at approximately 3,500 to 4,000 feet. This transition also includes a gradual increase in calcium levels downward. Groundwater in the lower Fort Union has lower salinity than does the upper portion of the formation with TDS concentrations of approximately 4,000 mg/L versus than 40,000 mg/L in the upper Fort Union; and is a sodium chloride/sodium bicarbonate type water versus a calcium chloride type (throughout the upper Fort Union).

As shown on the cross-section (Figure K-4), the surface casing for most of the wells is set at approximately 2,500 feet bgs, as required by the BLM (Rieman 2006). Some of the wells (Encana Hacienda 11-30 and 6-19, and Encana Holmes State 13-36) have shallower surface casings set at approximately 1,000 feet bgs. Geophysical well logs are generally not obtained within the surface casing in the upper part of the Wasatch Formation, but four wells in the JIDPA have well log data in the surface casing that were reviewed for shallow lithology. These logs show that the thickest sandstone beds in the JIDPA are found at depths of less than 800 feet, below which are thick sequences of layered shales and silts with a few thin sandstone beds. The high resistivity in these high-porosity sands indicates they contain water with low TDS.

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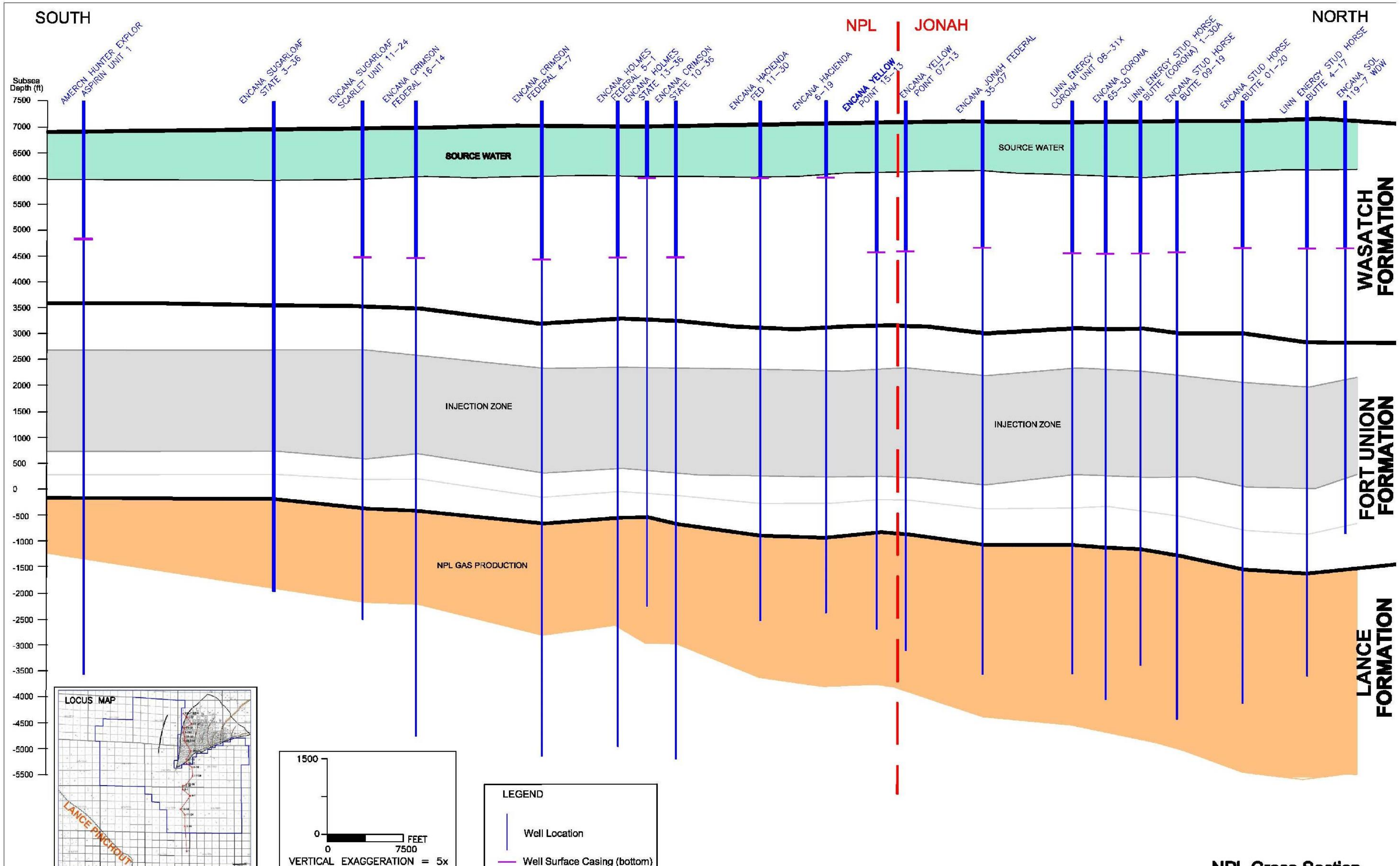
Figure K-4. South-North Geologic Cross Section through the NPL Project Area



Source: Modified from "Encana S-N Cross Section by DP DuBois", 2013

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4.0 EXISTING CONDITIONS OF WATER RESOURCES

This section provides a summary of water resources in the analysis area. Refer to Chapter 3 (*Affected Environment*) of the NPL Project EIS for more information on existing conditions for water resources.

4.1 Surface Water

Because it receives little runoff or precipitation, there are no permanent surface water features in the NPL Project Area, and drainage is mainly through ephemeral streams that receive runoff during spring snowmelt and rare storms events. Snowmelt from highlands surrounding the GRB watershed is the primary source of water to the basin. The meltwater drains off the mountain bases around the edges of the basin; however, the NPL Project Area is in the interior of the basin and does not receive much meltwater.

Fifteen HUC-12 watersheds intersect the NPL Project Area and contribute to five HUC-10 watersheds in the analysis area. All fifteen HUC-12 watersheds intersecting the NPL Project Area are drained by ephemeral streams and to a lesser extent by intermittent streams where there is a surficial alluvial aquifer. The major surface water bodies in the analysis area are the Green River, which runs north to south approximately six miles to the west of the NPL Project Area, and the Big Sandy River, which drains the area to the east of the NPL Project Area (Figure K-1). Table K-2 presents the total acreage of the watersheds in the analysis area as well as the acreages and percentages of the watersheds that occur within the NPL Project Area.

All drainages in the NPL Project Area are ephemeral and intermittent, which do not provide reliable water resources, and most intermittent streams only flow following snowmelt and precipitation events (WWDC 2014). There are surface expressions of groundwater, but none that produce perennial surface flows that reach other surface waters (BLM 2013a). Reservoirs and impoundment structures are present throughout the analysis area, but none contain permanent water. These impoundments accumulate water in response to precipitation events. Most of the water is lost to evaporation and a minor amount to recharge. These structures are range improvements used for livestock and sedimentation/flood control. WWDC (2014) stated in its analysis the Upper Green Watershed, in which part of the Project Area is located, produces excess water that could be beneficially utilized with additional storage capability.

Two unnamed groundwater springs within the NPL Project Area, along with the North Sublette Meadow Spring and Juel Spring outside the NPL Project Area boundary, discharge to ground surface. Locations of the springs are shown on Figure K-1. The two unnamed springs are in the Lower Alkali Creek and Long Draw watersheds. North Sublette Meadow Spring and Juel Spring are just east of the NPL Project Area boundary in the Jonah Gulch watershed. Field observation has indicated the presence of several shallow seeps and springs in the Teakettle Dune Field Area (Drucker 2016); however, these areas have not been mapped. The characteristics and water quality of springs in the analysis area is discussed in Section 4.2.2 (*Water Quality*) below, where data are available.

Although limited available data on ephemeral stream water quality are available for southwestern Wyoming, surface water quality can be both spatially and temporally variable in the arid high plains. No surface water quality data from within the Project Area were identified; however, general surface water quality can be inferred from the receiving perennial waters of the drainage area, which are the Green and Big Sandy Rivers. There were no reportable spills to the BLM found during a record search. If a spill does occur, it will be cleaned to WDEQ standards. The quality of runoff is largely dependent upon the amount of salts, sediments, and organic materials that accumulate in dry stream channels during periods of runoff. The degree to which these materials buildup between runoff events is influenced seasonally by physical characteristics of the soils (described in Section 3.15 (*Soil Resources)* of the NPL Project EIS) and land uses occurring within the watershed. The Green and Big Sandy Rivers experience the highest flows during spring snowmelt, and in the summer following thunderstorm events.

The Green and Big Sandy Rivers are classified by the WDEQ WQD as Class 2AB waterbodies (WDEQ 2014), which are known to support game fish populations or spawning and nursery areas at least seasonally and are protected for nongame fisheries, fish consumption, aquatic life other than fish, recreation, wildlife, industry, agriculture, and scenic value uses (WDEQ 2007). Neither the Big Sandy River nor the Green River appears on the State 303(d) list of impaired waters, and neither have existing TMDLs (WDEQ 2014).

In general, TDS is a water quality concern in the GRB and in the larger context of the Colorado River drainage area. However, TDS measurements for the Green River are relatively low (500 mg/L), although high TDS values (up to 3,000 mg/L) have been reported in downstream reaches of the Big Sandy River (Wyoming Water Development Office 2012). Surface water quality is generally better near the mountain ranges than in the lowlands. As runoff flows downstream from mountain ranges and over alkali soils in the basin flatlands, dissolved solids are accumulated and are transported downstream. Additional sources of dissolved solids may include agricultural runoff and other human activities.

The BLM has performed proper functioning condition (PFC) assessments for portions of two waterbodies in the analysis area: Alkali Creek and the Big Sandy River. The PFC assessment is a method for assessing hydrology, vegetation, and erosion/deposition attributes to determine the condition of riparian and /or wetland areas along a stream or river segment at a given point in time (Prichard et al. 1998). The PFC assessment is qualitative and is based on a checklist to make a relatively quick determination of condition. Following completion of the assessment, the stream segment is placed in one of the following categories: proper functioning condition; functional – at-risk; or, nonfunctional.

In 1998 and 2001, a total of approximately 5.5 miles of Alkali Creek were assessed in Sections 32 and 33 of T30N, R110W. All 5.5 miles of Alkali Creek assessed were determined to be functional – at-risk due to poor riparian vegetation cover, excessive erosion, and headcutting. Between 1994 and 2010, approximately 51 miles of the Big Sandy River were assessed using the PFC methodology; some of the assessed segments were located adjacent to the NPL Project Area. The majority (approximately 28.5 miles) of the segments assessed for the Big Sandy River were determined to be PFC, with approximately 18.8 miles functional – at-risk and another 3.8 miles unrated. Portions of the Big Sandy River adjacent to the NPL Project Area rated functional – at-risk exhibited high width to depth ratios, narrowing riparian vegetation cover, bank instability, and high sedimentation rates at the time of the assessments.

The *AGWA Technical Report* (Appendix J) identified 435 miles of stream channels within eight Watershed Modeling Units, encompassing all of the NPL Project Area and portions of all 15 HUC-12 watersheds comprising the water resources analysis area. Approximately 197 miles of these stream channels are represented by ephemeral drainages within the NPL Project Area.

Table K-2. Acreage of Watersheds in the NPL Project Area

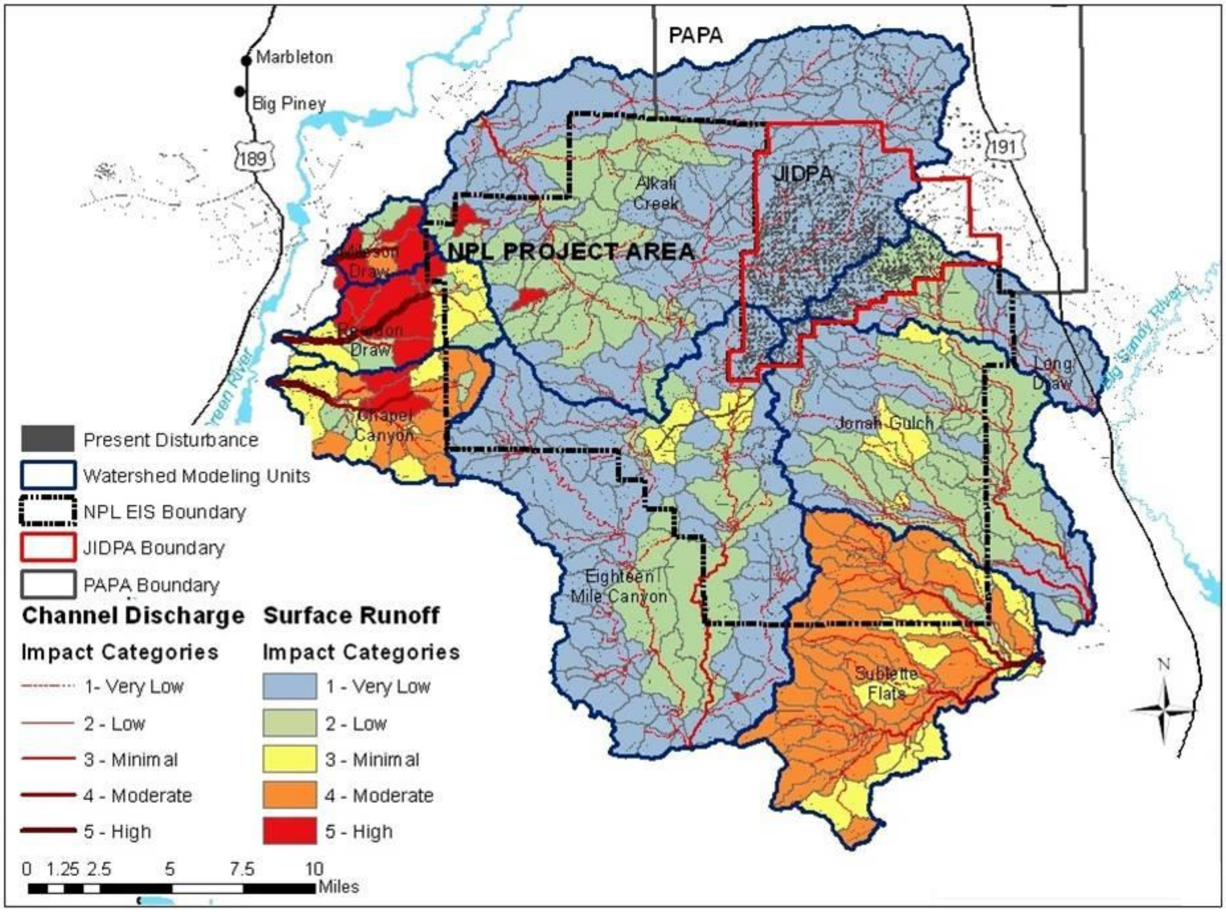
Watershed Unit	Total Watershed Acreage	Acres in the NPL Project Area	Percent of Watershed in the NPL Project Area
Alkali Creek (HUC 1404010106)	103,985	48,739	46.87%
Granite Reservoir (HUC 140401010603)	12,212	8,626	70.64%
Lower Alkali Creek (HUC 140401010605)	26,132	16,269	62.26%
North Alkali Draw (HUC 140401010604)	15,911	652	4.10%
Sand Draw Reservoir Number 4 (HUC 140401010601)	22,932	190	0.83%
Upper Alkali Creek (HUC 140401010602)	26,798	23,002	85.84%
Eighteenmile Canyon (HUC 1404010303)	211,311	35,025	16.57%
Lower West Buckhorn Draw (HUC 140401030303)	19,292	249	1.29%
Upper Eighteenmile Canyon (HUC 140401030301)	35,213	23,170	65.80%
Upper West Buckhorn Draw (HUC 140401030302)	21,746	11,605	53.37%
Birch Creek-Green River (HUC 1401040111)	233,326	5,601	2.40%
Chapel Canyon (HUC 140401011106)	14,357	2,036	14.18%
Reardon Draw (HUC 14041011105)	12,363	3,453	27.93%
Spring Creek-Green River (HUC 140401011104)	30,117	112	0.37%
Sublettes Flat (HUC 1404010404)	151,074	45,172	29.90%
Jonah Gulch (HUC 140401040401)	22,652	14,081	62.16%
Little Colorado Well No 9 (HUC 140401040403)	41,997	13,637	32.47%
Teakettle Butte (HUC 140401040402)	24,559	17,454	71.07%
Upper Big Sandy River (HUC 1404010401)	247,889	6,322	2.55%
Long Draw (HUC 140401040108)	18,522	6,273	33.87%
Bull Draw-Big Sandy River	19,761	49	0.25%

Source: USGS 2015b.

HUC Hydrologic Unit Code

The results of the AGWA modeling for the NPL Project indicate areas within the NPL Project Area that would be most susceptible to increased erosion, surface runoff, and sediment transport. As depicted in Figure K-5, there is generally very low runoff and channel discharge in the NPL Project Area. The comparatively large size of the area combined with low amounts of precipitation and surface runoff indicate that an individual storm event of reasonable size has a low probability of transporting sediment and associated salt from large or distant areas of contributing watersheds to major stream channels, such as the Green River and the Big Sandy River. However, areas with higher vulnerability to surface and channel erosion were identified at Sublette Flats, Reardon Draw, Mileson Draw, and Chapel Canyon. Refer to the NPL Project *AGWA Technical Report* (Appendix J) for more information resulting from the AGWA modeling for the NPL Project.

Figure K-5. Surface Runoff and Channel Discharge – Existing Conditions



Source: BLM 2013a.

4.2 Groundwater

4.2.1 Hydrogeology

The major structural features and resulting depositional patterns of the GRB influence the hydrologic characteristics of the NPL Project Area. Topography in the GRB follows undulations of the Precambrian basement. The thick sequences of Cretaceous- and Eocene-age shale, carbonate rock, and sandstone, which contain the primary aquifers for the area, thicken to the northeast and are exposed at the surface near the edges of the basin (Clarey 2010). In some areas, more recent unconsolidated sand and gravel alluvium with varying amounts of less permeable silts and clays form a surficial aquifer; however, these deposits are mainly limited to areas adjacent to the main riverbeds and washes. Similarly, groundwater conditions are highly variable in the Upper Green River Watershed due to variable geologic and hydrogeologic conditions. Refer to the Upper Green Level I Watershed Study (WWDC 2014) for more information on hydrogeologic conditions in the Upper Green Watershed. Refer to Section 3.6 (*Geology and Mineral Resources*) of the NPL Project EIS for more information on geology in the analysis area.

More recent alluvial deposits form localized saturated zones, mainly limited to areas in the bottomlands along the Green River west of, and the Big Sandy River east of, the NPL Project Area. Discontinuous alluvial aquifers exist to a limited extent in the floors of intermittent stream valleys in the Tea Kettle Butte watershed, located in the southeast portion of the Project Area (Figure K-1) (Bartos and Hallberg 2010).

Permeable water-bearing rocks of Lower Tertiary age make up the Lower Tertiary Aquifer and include the Laney Member of the Green River Formation, the Wasatch Formation, and the Fort Union Formation. Based on field observations by Winterfeld (2011) and other data, the Wasatch Formation occurs at ground surface in the northern portions of the NPL Project Area, and the Laney Member of the Green River Formation is exposed at the surface in the southern portion of the NPL Project Area. Water flowing south in the Wasatch Aquifer recharges the Laney Aquifer across a gradational formation contact. The Laney Member is only an important aquifer locally at the edge of the analysis area near the Big Sandy River, where it is fractured and/or contains solution-enhanced permeability. In the NPL Project Area, the Laney Aquifer is thin (less than 200 feet), the hydraulic conductivity is low, and well yields are small (Martin 1996).

The sections below describe the Wasatch Aquifer within the analysis area that could be affected by development of the NPL Project. Information presented in the sections below comes primarily from the Wyoming Water Development Commission and Wyoming State Geological Survey (Bartos and Hallberg 2010; Bartos et al. 2010; Clarey 2010; Clarey and Copeland 2010; Clarey and Thompson 2010; WSGS 2010) and are highly generalized in nature. These sources represent the best readily available existing information, which is often regional in nature and not specific to the NPL Project Area. As a result, all information may not reflect the site-specific conditions within the NPL Project Area. Additional information on NPL Project Area specific conditions will continue to be collected during development and implementation of the groundwater monitoring program for the NPL Project and other efforts prior to and during development.

The Mesaverde Aquifer is continuous with and considered part of the Lower Tertiary Aquifer system, although it is stratigraphically below the Lower Tertiary and is Mesozoic age (Cretaceous). The aquifer includes the Lance-Fox Hills Aquifer, the Lewis Confining Unit, and the Mesaverde Aquifer. It is underlain by the Baxer-Mowry Confining Unit, which is 5,000 to 12,000 feet thick in the GRB (Bartos and Hallberg 2010). The saturated thickness of the Mesaverde Aquifer is over 2,000 feet thick in the NPL Project Area. The Mesaverde aquifer is below the Lance Pool and is a potential source of produced formation fluids if identified as a targeted formation and if wells are completed below the Lance Pool.

4.2.1.1. Hydraulic Characteristics of the Wasatch Aquifer

The Wasatch Aquifer is the main source of groundwater in the analysis area. Water for livestock and potable uses is drawn from the shallower depths of the formation. Wasatch strata are present at ground surface (i.e., outcrops) in the northernmost, westernmost, and easternmost portions of the NPL Project Area (Winterfeld 2011) and are buried in the southern portions of the NPL Project Area, as shown on Figure K-6 (Bartos and Hallberg 2010). The Wasatch Formation is a sequence of a fluvial sandy shale and siltstone with few channel sands and coal deposits. The sandstone lenses are spatially limited and are generally not able to be correlated between two adjacent wells. The hydraulic characteristics of the Wasatch Aquifer reported by Bartos and Hallberg (2010) for a broad area of the GRB indicate large variations in groundwater flows and yields, representing the heterogeneity of the aquifer (Table K-3).

Table K-3. Hydraulic Characteristics of the Lower Tertiary Aquifers

Hydrogeologic Unit	Range of Hydraulic Conductivity (feet per day)			Well Yields (gpm)
	Simulated		Measured	Measured
	Vertical	*Horizontal*	*Horizontal*	
Laney Aquifer	0.00001 – 17.3	0.04 - 17.3	2 - 1,400	2 - 2,250 (median = 17)
Wasatch Aquifer	0.001 – 4	0.04 - 6.5	0.03 - 2,100	2 - 302 (median = 20)
Fort Union Aquifer	0.00001 - 0.01	0.00001 - 0.3	0.02 - 1,100	5 (only one measurement)

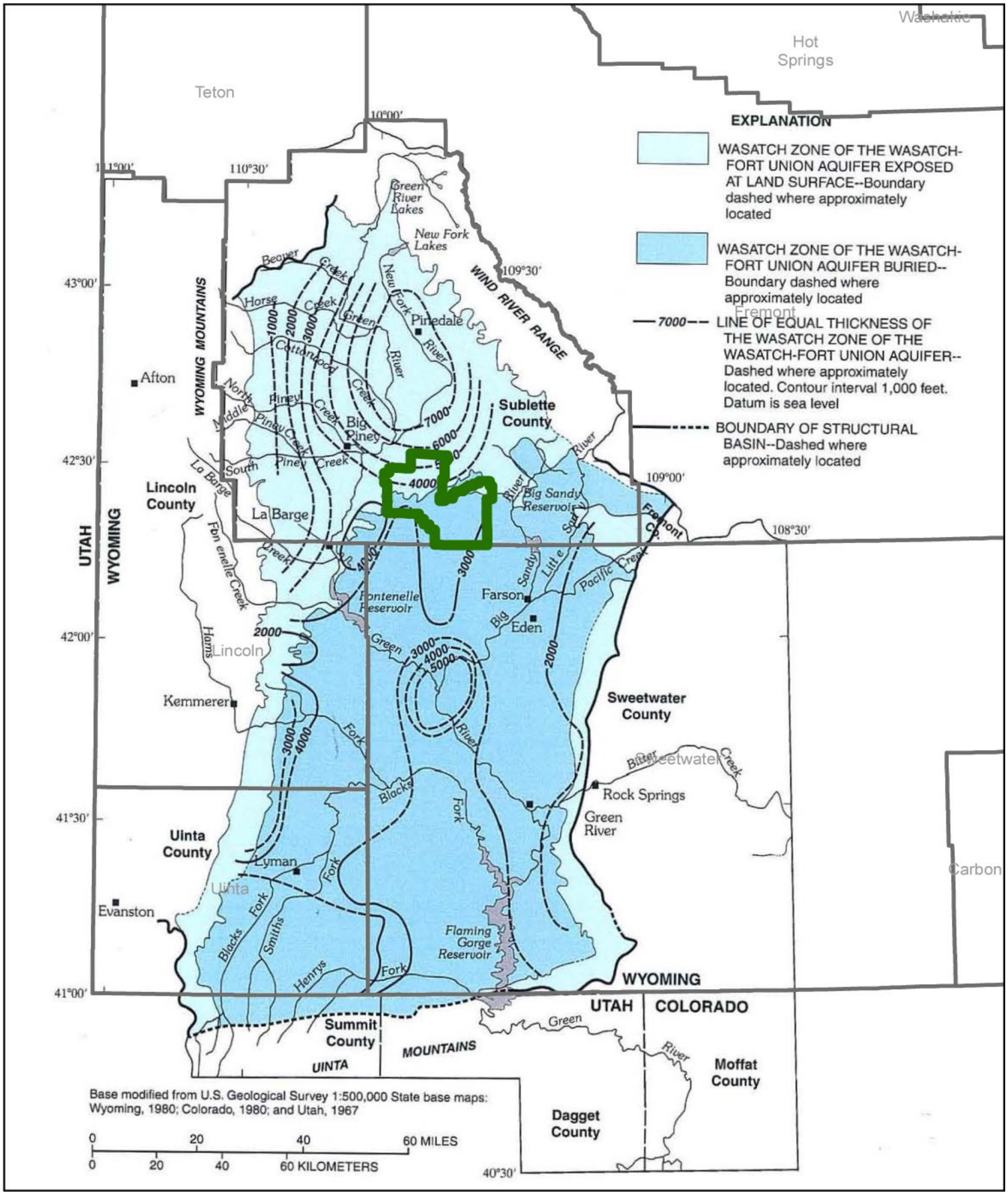
Source: Bartos and Hallberg 2010.

gpm gallons per minute

Aquifer tests were conducted in eleven industrial supply wells to support the PAPA Hydrologic Model (AMEC 2013a). The wells were completed within the Wasatch Aquifer and included screened intervals between 110 and 795 feet below surface. Hydraulic conductivity derived from the aquifer tests ranged from 0.02 to 9.5 ft/day (AMEC 2013a). The data also indicated that the hydraulic conductivity decreases in the lower Wasatch due to increased volumes of silt and clay. Industrial water supply wells producing from the Wasatch typically average around 150 gpm (AMEC 2013a). The JIDPA Hydrologic Model (HydroGeo 2004) uses a range of hydraulic conductivities similar to those measured at PAPA: 1.6 ft./day in the lower Wasatch and 9.5 ft./day in the upper Wasatch. No aquifer testing has been conducted within the NPL Project Area. The range of hydraulic conductivity values for the Wasatch Aquifer reported by Bartos and Hallberg (2010) is consistent with the results used for the PAPA and JIDPA numerical models, and is expected to be representative of the Wasatch Aquifer in the NPL Project Area.

Water quality in the Wasatch Formation is both spatially and vertically variable (Bartos et al. 2010). While the water quality in the shallow zones (less than 1,000 feet) generally meets the U.S. Environmental Protection Agency's (EPA 2009) Primary or Secondary MCL standards for domestic use and Wyoming Department of Environmental Quality's (WDEQ 2015) Class 2 and 3 standards for agriculture and livestock use, some naturally occurring constituents, such as fluoride, radon, arsenic, and boron are locally present at concentrations above these standards (Bartos et al. 2010; WWDC and University of Wyoming 1990). Refer to Section 4.2.2 (*Water Quality)* below for more information on groundwater quality in the Wasatch Aquifer.

Figure K-6. Wasatch Aquifer: Areal Extent and Thickness (including Project Area)



Source: Bartos and Hallberg 2010.

4.2.1.2. Hydraulic Characteristics of the Fort Union Aquifer

Throughout the analysis area, the Fort Union Formation underlies the Wasatch Formation and is mainly composed of fluvial sandstones, sandy shales, and siltstones interbedded with channel sands, lignite, and coal. The Fort Union Aquifer is approximately 4,000 feet thick and is not exposed at the surface in the analysis area. There are limited existing data or aquifer studies of the Fort Union Formation. Estimates of hydraulic characteristics of the Fort Union Aquifer were developed based on field data within the GRB and a basin scale groundwater model simulation (Martin 1996) and are not specific to the NPL Project Area. There is currently no readily available information on transmissivity specific to the NPL Project Area. Estimates of hydraulic conductivity in the Fort Union Aquifer vary widely due to the heterogeneity of the lithology (Table K-3), and the simulated hydraulic conductivities derived for the Fort Union Aquifer are orders of magnitude below those of the Wasatch Aquifer. In the 2011 WOGCC application for injection into the Lower Fort Union in the Jonah Hacienda 4-1, Encana stated that the porosity of the sands was approximately 17 percent and estimated the permeability to be between 1 and 5 millidarcies (Encana 2011a). The geologic description from logs in the Jonah and PAPA supporting the application stated the Fort Union was dominated by mudstones. There are very few wells that draw from the aquifer, and only one value of 5 gallons per minute (flowing) is reported for the Fort Union (Bartos and Hallberg 2010).

4.2.2 Water Quality

The sections below provide a summary of the best available existing information for water quality for wells in and around the NPL Project Area (Figure K-7). The water quality presented in this section focuses on the key analytes, parameters, and water quality characteristics for wells that target the alluvial aquifer, Laney Aquifer, and the Wasatch Aquifer and the Fort Union. Figure K-7 depicts the location of water wells that have been tested for certain water quality analytes by the operator's sampling and analysis program and water supply wells in the JIDPA that have been sampled as part of ongoing sampling in the JIDPA.

In addition, select water quality information from water wells for the most recent year sampled prior to 2014 is presented in Figure K-8 for representative wells (i.e., wells that covered the geographical range of the analysis area and had a detectable level of one or more analyte). Figure K-8 depicts the concentrations of methane, total dissolved solids (TDS), benzene, chlorides, total petroleum hydrocarbons - diesel range organics (TPH-DRO), and total petroleum hydrocarbons - gasoline range organics (TPH -GRO) in relation to established standards or limits. These standards and limits were chosen for comparison based on primary uses in the analysis area (e.g., there is high prevalence of livestock water use around the analysis area, therefore the WDEQ Class III – Livestock Use Suitability standard was chosen), safety standards (e.g., certain thresholds of methane are established due to risk of an explosion), and groundwater cleanup levels. Some of these standards overlap with EPA Primary or Secondary Drinking Water Standards, which are also described here as appropriate or where other standards do not exist. Data for wells sampled through 2014 by Trihydro (2011, 2013, 2014a, 2014b) as part of the NPL Groundwater Monitoring Program have been identified in the following sections. At the time of this report, there were no 2014 data available for wells in the Jonah Field. Refer to Attachment C (*Water Quality Results from Water Wells in and Around the Project Area*) for detailed information including measurements that have exceeded regulatory standards and limits.

Water quality information from wells presented in Attachment C (*Water Quality Results from Water Wells in and Around the Project Area)* was gathered from AECOM 2014; AMEC 2014; Trihydro 2011, 2013, 2014a, 2014b; and Wyoming SEO 2014. This information represents existing conditions and is depicted on Figure K-8. From these data, select wells, which are presented in Figure K-8, indicate several trends, including:

- Methane was detected in wells located in the central- to south-eastern portion of the analysis area, with four wells exceeding 5 mg/L (Figure K-8). Concentrations of methane above 5 mg/L warrant isotope analysis to help identify potential sources. There are no drinking water or groundwater standards established for methane.
- TDS was detected in wells throughout the analysis area but in larger concentrations throughout the western portion of the analysis area. Only one well exceeds the WDEQ Class III – Livestock Use Suitability standard of 5,000 mg/L (Map Reference #50 on Figure K-8). This standard was chosen for purposes of comparison because of the high prevalence of livestock water use in and around the Project Area. The primary component of TDS is sulfate.
- Benzene was detected in three wells in the central-north portion of the analysis area (Figure K-8). Only one well (Corona 2-14, Map Reference #61 on Figure K-8) exceeds the EPA Primary Drinking Water Standard and Wyoming Groundwater Cleanup Level of 5 µg/L. These are the only standards available for benzene, which is health concern in drinking water.
- Chlorides were detected in wells throughout the analysis area, with the largest concentrations found throughout the southeastern portion (Figure K-8). Two wells exceed the EPA Secondary Drinking Water Standard, Wyoming Groundwater Cleanup Level, and WDEQ Class I – Domestic Use Suitability standard of 250 mg/L (Map Reference #3 and 43 on Figure K-8). These standards are presented because WDEQ Class III – Livestock Use Suitability standard is 2,000 mg/L, and no wells exceeded this standard.
- TPH-DRO (hydrocarbon) was detected in six wells at very low concentrations, with the majority of wells with detected levels being in the western portion of the analysis area (Figure K-8). None of the wells exceed the Wyoming Groundwater Cleanup Level of 1.1 mg/L (if benzene is present) or 10 mg/L (if benzene is absent). There are no additional established drinking water standards for DRO.
- TPH-GRO (hydrocarbon) was detected in eight wells at very low concentrations, with the majority of wells with detected levels to the north-western portion of the analysis area (Figure K-8). None of the wells exceeded the Wyoming Groundwater Cleanup Level of 7.3 mg/L. There are no additional established drinking water standards for GRO.

Refer to Attachment C (Water Quality Results from Water Wells in and Around the Project Area) for more information on water quality for all wells where data are available and a summary of regulatory standards or limits for water quality parameters.

Figure K-7. Water Quality Sampling Locations

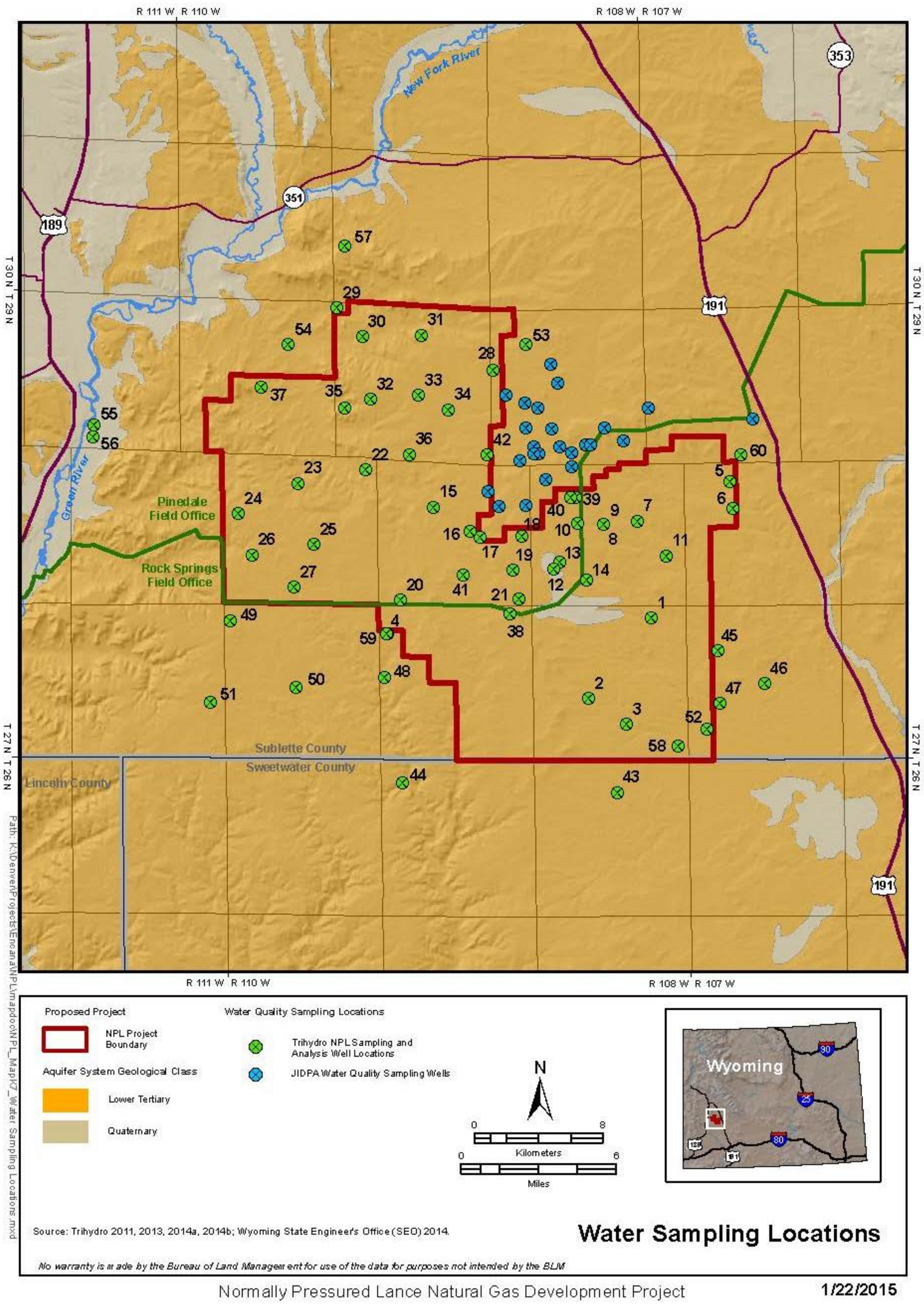
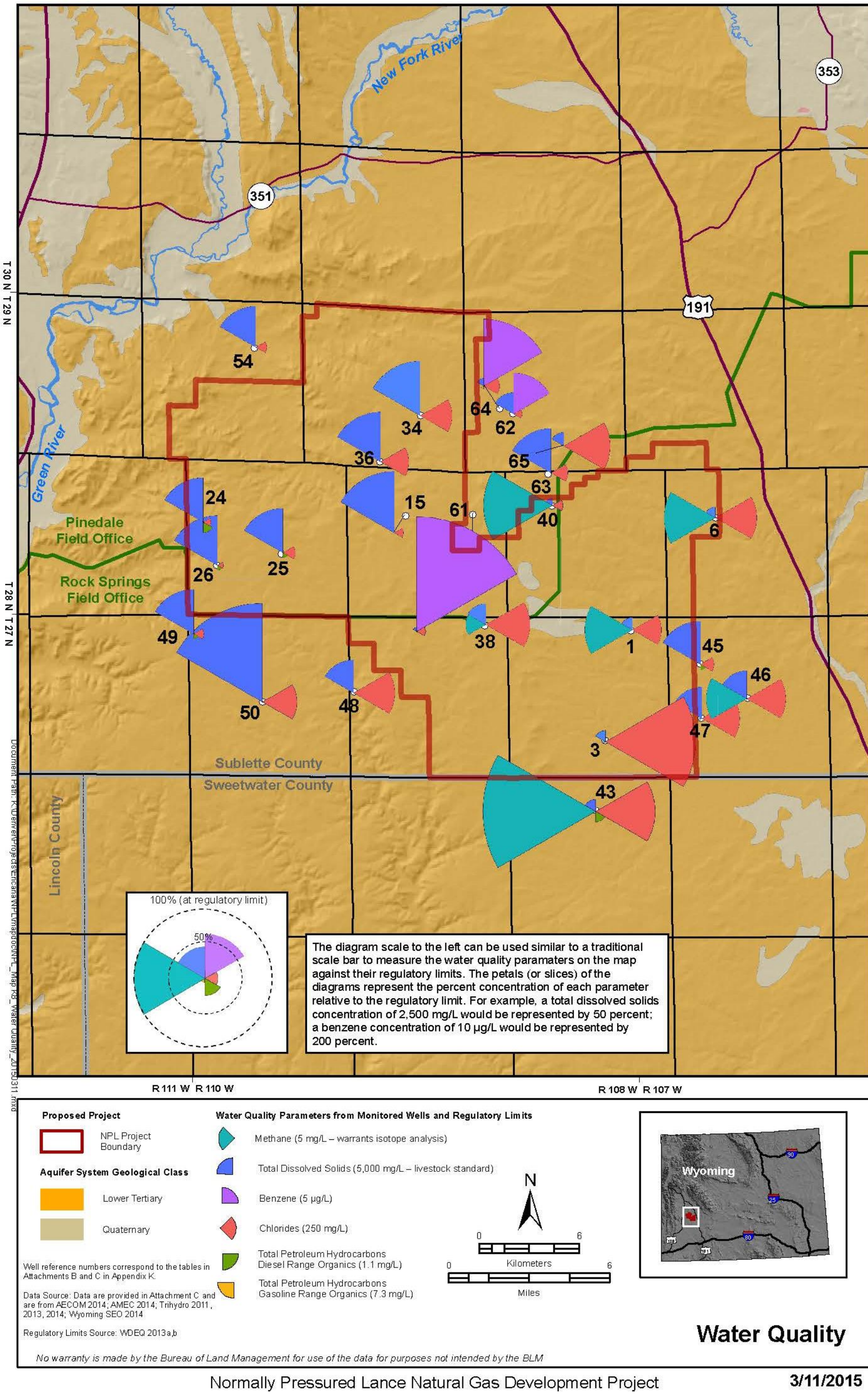


Figure K-8. Water Quality Summary of Representative NPL and JIDPA Wells



4.2.2.1. Alluvial Aquifer

Most wells in the NPL Project Area and JIDPA are completed in the upper 1,100 feet of the Wasatch Formation due to the favorable hydrologic properties in the upper strata; however, some wells and springs are interpreted to have source zones in the Alluvial Aquifer. Wells and springs are identified as alluvial sources if they were shallow (less than 150 feet) and adjacent to a river or stream (Trihydro 2011). No field or hydrological studies have been conducted to verify the water source relationships for the sampling points interpreted to be alluvial from the operator's sampling and analysis program. Sampling and analysis of existing wells and springs in the NPL Project Area (Figure K-7) (Trihydro 2011, 2013, 2014a, 2014b) provide the best available data for assessing water quality from the alluvium. Some alluvial aquifers may be recharged by underlying or adjacent zones including the Wasatch and Laney. Alluvial sources with water quality data include the following wells in or adjacent to the NPL Project Area: NA1, P9437, and McGinnis2 as identified in Attachment C (*Water Quality Results from Water Wells in and Around the Project Area*). North Sublette Meadow Spring, located immediately adjacent to the east boundary of NPL Project Area, is also likely sourced from the alluvium (Figure K-1). Attachment B (*Water Supply Wells in and around the NPL Project* Area) provides available water quality information for alluvial sources noted above, and Figure K-8 provides a summary of water quality.

Water quality in the Alluvial Aquifer is similar to the Wasatch, as described below. The water is a sodium sulfate to sodium bicarbonate composition. Elevated TDS, pH, sulfate, iron, and manganese are present in some wells and springs above U.S. EPA Primary Drinking Water Standards (EPA 2009). North Sublette Meadow Spring (Map Reference #45 on Figure K-8) contained detectable levels of TPH – DRO in 2011, 2013, and 2014 (Trihydro 2011, 2014a, 2014b), and well NA1 exhibited a low concentration of TPH – GRO in 2013 (Trihydro 2014a). Refer to Attachment C (*Water Quality Results from Water Wells in and Around the Project Area*) for more information on water quality, by well.

4.2.2.2. Wasatch Aquifer

The Wasatch Aquifer would provide water for the NPL Project from existing water supply wells in the JIDPA and NPL Project Area (Figure K-2) and potential new water supply wells in the NPL Project Area. Water quality data for the Wasatch Aquifer is described below for the upgradient area (JIDPA and PAPA), the NPL Project Area, and the areas adjacent to the NPL Project Area on the south, east, and west boundaries of the NPL Project Area. Water quality data for the Wasatch Aquifer were obtained from water supply wells in the JIDPA that draw from the Wasatch Aquifer and are summarized in Tables K-4 and K-5 and detailed in Attachment C (*Water Quality Results from Water Wells in and Around the Project Area*).

Water quality, represented by the TDS content, generally decreases in the deeper parts of the aquifer (Bartos et al. 2010). Analysis of well log data (Phillips 2013b) from the Wasatch in the JIDPA (well SHB 1-20, located in T29N, R108W, Section 20) shows high resistivity in the upper sands (0 to 1,000 feet below surface), corresponding to freshwater, and low resistivity in water bearing sands in the lower Wasatch (2,500 to 4,000 feet below surface) indicates higher TDS content. The BLM (Onshore Order No. 2) considers any groundwater from fresh (<1,000 mg/L) to moderately saline (<10,000 mg/L) as usable water, which is to be protected. Regulations from 40 CFR Section 144.3 indicate that all groundwater with TDS less than or equal to 10,000 mg/L are presumed to be an underground source of drinking water (USDW) and must be protected unless an aquifer exemption has been granted under the Safe Drinking Water Act (SDWA). Water samples from the underlying Fort Union at depths of 5,000 to 6,500 feet below surface have TDS concentrations of approximately 50,000 mg/L (Table K-6). The downward increase in TDS from fresh water to Class IV (B), or lower water quality, is demonstrated; however, the exact depth at which the water exceeds a TDS concentration of 10,000 mg/L (the BLM criteria for usable water) has not been established. For the purpose of the analysis of potential impacts, it is assumed that all of the water bearing zones of the Wasatch in the analysis area contain usable water (TDS concentration less than 10,000 mg/L) unless otherwise demonstrated, and is protected in accordance with Onshore Order No. 2. It is also considered an USDW and is protected under the SDWA.

The operator's sampling and analysis program in the NPL Project Area is conducted annually for a limited number of parameters including specific conductivity, pH, TDS, alkalinity, chloride, barium, calcium, iron, magnesium, sodium, benzene, toluene, ethylbenzene, and xylenes (BTEX), TPH - DRO and TPH – GRO (Trihydro 2011, 2013, 2014a, 2014b). The wells and springs included in the sampling program were not specifically designed for groundwater monitoring and therefore the sampling results may not represent ambient groundwater conditions. Drilling practices, well construction materials, and well construction may affect the representativeness for the samples. In addition, diesel or gasoline powered generators were used to power pumps at some of the well locations, and operation and maintenance of these generators could result in releases of petroleum hydrocarbons, and as a result, affect the water samples. Water quality results from the operator's sampling and analysis program is presented as the best available existing information for water quality in the NPL Project Area.

Four rounds of annual sampling and analysis of water wells and springs have been conducted in and adjacent to the NPL Project Area (Trihydro 2011, 2013, 2014a, 2014b). Between 2011 and 2013, 50 samples were collected from 30 wells and springs (Trihydro 2014a). Most of the sampled wells are used for livestock watering and a few are used for domestic water supply. There are no industrial, agricultural, monitoring, or observation wells in the NPL Project Area. A subset of all wells in the area was sampled each year: 26 wells were sampled in 2011, 11 wells were sampled in 2012, and 13 wells were sampled in 2013, with some wells being sampled in multiple years. Under the revised WOGCC Baseline Water Quality Sampling Plan, 21 wells were sampled in 2014. Water samples were initially analyzed for a wide range of analytes including general parameters, dissolved metals, general organics, dissolved gases, radiological, bacteria, alcohols, and glycols. Subsequent rounds of sampling events include a more limited list of indicator analytes with a provision to expand the analyte list if indicator compounds exceed established thresholds (Trihydro 2013). Fluoride was not sampled in 2011 (Trihydro 2011), but was added and included in the 2012 through 2014 analyte lists (Trihydro 2013, 2014a, 2014b). Arsenic was analyzed in 2011 and 2012 but was not analyzed subsequently. VOCs were analyzed using EPA Method 8260B, a gas chromatography/mass spectroscopy (GC/MS) method that is less likely to result in the misidentification of benzene, which may occur when using GC-only analytical methods such as EPA Method 8021B (AMEC 2013b). Results of the sampling and analysis program are summarized below, and results are presented by well in tabular format in Attachment C (*Water Quality Results from Water Wells in and Around the Project Area*). Refer to the TriHydro Sampling and Analysis Reports for piper diagrams of water chemistry for wells sampled in 2011-2014 (Trihydro 2011, 2013, 2014a, 2014b).

Select water quality parameters (based on the highest frequency of detected values and those parameters with established drinking water and groundwater standards from the EPA (2009) and WDEQ (2013)) for wells sampled in 2013 are presented in Figures K-10, A-L as boxplots by field to show the variation, median (i.e., typical value), minimum and maximum observations, and outliers. These boxplots are presented together at the end of this section to allow for side-by-side comparison of analytes.

Table K-4 Summary Statistics for Jonah Water Supply Wells, 2013

	Well Depths (ft. bgs)	Water Level (ft. bgs)	Temp °C	pH	Conductivity (µS/cm)	Total Dissolved Solids (mg/L)
Min	510	70	8.0	8.4	557	286
Max	2,310	360	16.3	10.5	5,660	4,370
Average	869	180	10.9	9.4	1,534	945

Source: AMEC 2014; AECOM 2014; Trihydro 2014a; USGS 2010; Wyoming SEO 2014.

Note: Data used to generate these statistics are found in Table K-5.

°C degrees Celsius
ft. bgs feet below ground surface
mg/L milligrams per liter
µS/cm micro Siemens per centimeter

Table K-5. Annual Groundwater Monitoring Results from Water Supply Wells in the Jonah Field, 2013

Well Identification	Total Depth (ft. bgs)	Water Level (ft. bgs)	Date	Field Temperature (Celsius)	Field pH (SU)	Field Conductivity (µS/cm)	Total Dissolved Solids (mg/L)
Cabrito 13-19W	900	360 [b]	11/8/2013	10.03	**10.0** [f]	570	**308** [d]
Jonah Fed 2-5W	920	167 [c]	11/6/2013	10.04	**8.6** [f]	2,500	**1,690** [d]
Jonah Fed 2-7W	745	220 [b]	11/6/2013	10.17	**9.2** [f]	1,640	**1,010** [d]
Jonah Fed (SHB) 32-34	1,000	300 [b]	11/6/2013	10.97	**9.6** [f]	1,090	**656** [d]
Stud Horse Butte 122-10	740	150 [b]	11/8/2013	8.89	**9.8** [f]	863	**514** [d]
Stud Horse Butte 11-20W	760	150 [b]	11/7/2013	9.63	**9.4** [f]	986	**565** [d]
Stud Horse Butte 11-26W	735	346 [c]	11/5/2013	11.04	**9.5** [f]	872	**466** [d]
Stud Horse Butte 10-28W	900	135 [b]	11/7/2013	9.47	**9.2** [f]	1,080	**591** [d]
Stud Horse Butte 11-29W	615	109 [c]	11/7/2013	8.03	**8.9** [f]	2,670	**1,870** [d]
Stud Horse Butte 7-32W	940	70 [b]	—	—	—	—	—
Stud Horse Butte 9-32W	700 [a]	100 [a]	11/8/2013	9.77	**8.4** [f]	2,480	**1,910** [d]
Stud Horse Butte 10-32W	940	140 [b]	11/8/2013	8.97	**9.0** [f]	2,250	**1,590** [d]
Stud Horse Butte 13-32W	740	320 [b]	11/8/2013	10.04	**8.5** [f]	3,430	**2,460** [d]
Stud Horse Butte 7-33W	1,100	120 [b]	11/7/2013	11.03	**9.4** [f]	949	**536** [d]
Stud Horse Butte 8-34W	900	280 [b]	11/6/2013	10.98	**9.8** [f]	854	**493** [d]
Stud Horse Butte 10-34W	1,000	160 [b]	11/6/2013	9.51	**9.6** [f]	1,060	**610** [d]
Stud Horse Butte 4-36W	960	189 [c]	11/9/2013	8.82	**9.7** [f]	660	**360** [d]
Yellow Point 10-11W	800	100 [b]	11/8/2013	10.78	**8.6** [f]	5,660	**4,370** [d]
Yellow Point 1-13W	575	150 [b]	11/7/2013	9.69	**9.3** [f]	1,700	**1,100** [d]
Wagon Road 1-26	800	90 [b]	—	—	**—**	—	**—**
Corona 2-14	973 [b]	250 [b]	9/12/2013	13	**10.5**	2,969	**453**
Jonah Field Office	640 [b]	130 [b]	9/12/2013	13	**9.29**	557	**286**

Table K-5. Annual Groundwater Monitoring Results from Water Supply Wells in the Jonah Field, 2013

Well Identification	Total Depth (ft. bgs)	Water Level (ft. bgs)	Date	Field Temperature (Celsius)	Field pH (SU)	Field Conductivity (μS/cm)	Total Dissolved Solids (mg/L)
Stud Horse Butte 15-16	680 [b]	145 [b]	9/12/2013	14	**9.91**	881	**439**
Stud Horse Butte 16-20	680 [b]	145 [b]	9/12/2013	12.7	**9.98**	1,022	**525**
Stud Horse Butte 23-16	1050 [b]	155	9/12/2013	16.3	**10.1**	562	**299**
Corona 7-19	900 [b]	265	9/12/2013	15.9	**10.3**	608	**320**
Holmes Federal 5-1W [e]	630	200	7/17/2013	—	**8.55**	1,130	**620**
Work Force Facility	1,100	—	7/16/2013	—	**9.05**	849	**540**
Plains WSW 2	510 [b]	150 [b]	—	—	—	—	—
Stud Horse Butte 14-32W	—	—	—	—	—	—	—
Stud Horse Butte 16-34W	2,310 [b]	200 [b]	—	—	—	—	—
SOL 9-36	920 [b]	175 [b]	—	—	—	—	—

Sources: AMEC 2014; AECOM 2014; Trihydro 2014a; USGS 2010; Wyoming SEO 2014.

[a]Assumed values were used because specific well information was not available.
[b]Information obtained from the State Engineers Office.
[c]Static water levels obtained using a sonic water level meter during 2009 annual groundwater monitoring event.
[d]Laboratory Analysis of total dissolved solids by Method A2540C.
[e]Water supply well for Jonah Field, but located in the NPL Project Area.
[f]pH measured in the laboratory.

ft. bgs feet below ground surface
mg/L milligrams per liter
SU Standard Units
μS/cm micro Siemens per centimeter

4.2.2.2.1. Petroleum Hydrocarbons

As part of the operator's sampling and analysis program in the NPL Project Area, wells were also sampled for general hydrocarbons (TPH-DRO and TPH-GRO using EPA Method 8015C). As indicated in Attachment C (Water Quality Results from Water Wells in and Around the Project Area), DRO was detected in four wells in 2013 in the NPL Project Area and two wells outside of the Jonah and NPL Project Area, with values ranging from 0.033 to 0.084 mg/L and 0.038 to 0.042 mg/L, respectively (Figure K-10G) (Trihydro 2014a). GRO was detected in one well in the NPL Project Area, and two wells outside of the JIDPA and NPL Project Area in 2013 (Figure K-10H). (Trihydro 2014a) These levels ranged from 0.011 to 0.326 mg/L. One of these sampling locations outside of the JIDPA and NPL Project Area is a spring – the North Sublette Meadow Spring. There are no EPA Primary or Secondary Drinking Water Standards for DRO or GRO. Wyoming has established Groundwater Cleanup Levels for DRO at 1.1 mg/L if benzene is present or 10 mg/L if benzene is not present, and for GRO at 7.3 mg/L (WDEQ 2013). None of the wells with detectable levels of DRO or GRO exceed these levels. It should be noted that the reporting levels for GRO and DRO were higher in 2011 and 2012 than in 2013; therefore DRO and GRO may have been present in the earlier sampling years, but in concentrations too low for detection or reporting (Trihydro 2011, 2013, 2014a). In 2014, 10 out of 16 wells in the NPL Project Area and four out of five wells outside of the NPL and Jonah Fields had detectable levels of DRO (Trihydro 2014b). No wells sampled in 2014 had detectable levels of GRO (Trihydro 2014b).

In 2013, low concentrations of petroleum hydrocarbons (including BTEX and TPH - GRO) were detected at JIDPA in five of the 24 wells sampled by Linn Energy and EnCana (Corona 2-14, Stud Horse Butte 16-20, Stud Horse Butte 11-20W [Map References 61, 62, and 64, respectively, on Figure K-8], Corona 7-19, and Stud Horse Butte 10-32W [not mapped]). These wells are located in the west central portion of the JIDPA and are hydrologically upgradient from the NPL Project Area (Figure K-8). Petroleum components have been detected in previous sampling rounds in other wells, but none were above U.S. EPA Primary Standards.

Petroleum hydrocarbons have been detected north of the JIDPA in the PAPA at concentrations above the U.S. EPA Primary Standards (AMEC 2013b). The water supply wells where organic constituents have been consistently detected at concentrations greater than applicable groundwater standards have been, or are currently, under regulatory oversight by the WDEQ through the Voluntary Remediation Program (AMEC 2013a). Extensive analysis of the presence of hydrocarbons at the PAPA concluded that there is no evidence that oil and gas operations have resulted in widespread impacts to groundwater in the PAPA. Hydrocarbons detected in the wells are the result of the following factors:

- Low level volatile organic compounds are largely attributable to upward seepage of natural gas from deep, underlying gas reservoirs over time into overlying geologic layers where groundwater occurs;
- The source of low level semivolatile organic constituents is not readily apparent but likely originates from substances introduced into water wells during drilling, installation, and operation of the well; or
- Naturally occurring organic matter in groundwater or associated with particles suspended in well water during sample collection (AMEC 2013a).

4.2.2.2.2. Total Dissolved Solids and Iron

As indicated in Attachment C (*Water Quality Results from Water Wells in and Around the Project Area),* TDS concentrations above the U.S. EPA secondary standards are present in many water supply wells in the JIDPA (Figure K-8) (Trihydro 2011, 2013, 2014a, 2014b). Elevated iron is also present in some wells. Elevated TDS and iron concentrations are a naturally occurring condition common within the Wasatch Formation (Bartos et al. 2010). As shown in Figure K-10, the ranges of TDS are similar between the Jonah and NPL Fields, with the typical (i.e., median) value for Jonah being the lowest among the group. In 2013, seven of the eight samples in the NPL Project Area indicate TDS levels above the EPA Secondary Drinking Water Standard and Wyoming Groundwater Cleanup Level of 500 mg/L for TDS (EPA 2009; Trihydro 2014a; WDEQ 2013), and in 2014, 14 out of the 16 samples exceeded these levels (Trihydro 2014b). Seventeen of the 27 samples for the JIDPA in 2013 indicated TDS levels above these standards, with an outlier at 4,370 mg/L and the next highest observation at 2,460 mg/L. All ten samples outside of the NPL and Jonah Fields (i.e., "other") in 2013 and 2014 indicated TDS levels above the standards, with a range of 570-1,540 mg/L. Only one well exceeds the WDEQ Class III – Livestock Use Suitability standard of 5,000 mg/L (WDEQ 2015) (Map Reference #50 on Map 33).

As indicted in Attachment C (*Water Quality Results from Water Wells in and Around the Project Area*), the typical ranges of total iron are similar among all the fields; however there are several significant outliers in the JIDPA, with the highest sample reaching 28.9 mg/L in 2013 (Figure K-10C) (Trihydro 2014a). This sample is well above the EPA Secondary Drinking Water Standard of 0.3 mg/L and above the Wyoming Groundwater Cleanup Level of 25.5 mg/L for iron (EPA 2009; WDEQ 2013). Nine of the 19 samples in the JIDPA in 2013 are above the EPA Secondary Drinking Water Standard and two are above the Wyoming Cleanup Level (Trihydro 2014a). In 2013, two of the six samples for the NPL Project Area and two of the five samples outside of the Jonah and NPL Fields are also above EPA standards; none of which are above Wyoming Groundwater Cleanup Levels. The minimum observations among the samples in the NPL Project Area and JIDPA are similar, with total iron values around 0.03-0.04 mg/L. Total iron was not part of the analyte list for wells tested in 2014 (Trihydro 2014b). Dissolved iron was only sampled in 12 wells in the JIDPA in 2013, with concentrations ranging from 0.03 to 3.8 mg/L (Figure K-10D) (Trihydro 2014a). Dissolved iron was sampled in all wells inside the NPL Project Area and all wells outside of the NPL and Jonah Fields in 2014; 11 out of 21 wells tested had detectable levels of dissolved iron, with concentrations ranging from 0.0105 to 1.15 mg/L (Trihydro 2014b). There are no drinking water or groundwater standards for dissolved iron.

4.2.2.2.3. Fluoride

As indicated in Attachment C (*Water Quality Results from Water Wells in and Around the Project Area)*, results of the of the water quality analyses show concentrations of fluoride above the EPA Primary Drinking Water Standard and Wyoming Groundwater Cleanup Level of 4.0 mg/L in three of the eight wells sampled in the NPL Project Area and two of the five wells sampled outside of the NPL Project Area and JIDPA (i.e., "other") in 2013 (Figure K-10E) (EPA 2009; Trihydro 2014a; WDEQ 2013). However, it should be noted that fluoride is known to be high and natural occurring in this area (WSGS 2010). The ranges of detected fluoride in both sampling areas in 2013 are similar, with minimum observations of 0.69 and 0.8 mg/L and maximum observations of 9.8 and 8.8 mg/L for the NPL Project Area and other area, respectively (Trihydro 2014a). Fluoride was detected in eight out of 16 wells in the NPL Area and two out of five wells outside of the NPL and Jonah Fields at levels greater than the drinking water and groundwater cleanup level of 4.0 mg/L (Trihydro 2014b). No wells in the JIDPA were sampled for fluoride in these analyses.

4.2.2.2.4. Sulfate and PH

As indicated in Attachment C (*Water Quality Results from Water Wells in and Around the Project Area),* sulfate and pH exceeded U.S. EPA Secondary Drinking Water Standards in several wells over the four year period (Trihydro 2011, 2013, 2014a, 2014b). As indicated in Figure K-10A, each field has samples that exceed the upper range of the EPA Secondary Drinking Water and Wyoming Groundwater Cleanup Level of pH 6.5-8.5 (EPA 2009; WDEQ 2013) in 2013, with samples in the JIDPA having some of the highest observations of up to pH 10.5 (Trihydro 2014a). These high levels may be due to pH being measured in Jonah samples from AMEC (2014) in the laboratory, rather than the field; however, some of these samples with lower pH levels are similar to those in the other fields. Overall, 25 of the 27 wells in the JIDPA, five of the eight wells in the NPL Project Area, and three of the five wells in other areas exceed the upper limit (pH 8.5) of the EPA and Wyoming standards in 2013. In 2014, nine out of 16 wells in the NPL area and three out of four wells outside of the NPL and Jonah Fields exceeded the upper pH limit of 8.5 (Trihydro 2014b).

4.2.2.2.5. Metals

As indicated in Attachment C (*Water Quality Results from Water Wells in and Around the Project Area*), in 2011, 2012, and 2013, wells in the NPL Project Area were tested for a variety of metals, including arsenic, boron, manganese, and selenium (Trihydro 2011, 2013, 2014a). In 2014, wells were tested for boron, manganese, and selenium. One well had a detectable concentration of arsenic in 2011 at 0.0901 mg/L, which is above the EPA Primary Drinking Water Standard and Wyoming Groundwater Cleanup Level of 0.01 mg/L. Two wells in 2012, one well in 2013, and two wells in 2014 had boron concentrations above the Wyoming Groundwater Cleanup Level of 0.75 mg/L (Trihydro 2013, 2014a, 2014b). Eight wells in 2011 and four wells in 2014 had detectable levels of manganese above the EPA Secondary Drinking Water Standard and Wyoming Groundwater Cleanup Level of 0.05 mg/L (EPA 2009; WDEQ 2013). One well in 2011 had a detectable level of selenium at 0.157mg/L, which is above the EPA Primary Drinking Water Standard and Wyoming Groundwater Cleanup Level of 0.05 mg/L.

4.2.2.2.6. Benzene, Toluene, Ethylbenzene, Xylenes

As indicated in Attachment C (*Water Quality Results from Water Wells in and Around the Project Area*), benzene was detected in four wells in the JIDPA, with concentrations ranging from 1 to 11.8 µg/L in 2013 (Figure K-8). The EPA Primary Drinking Water Standard and Wyoming Groundwater Cleanup Level for benzene is 5 µg/L (EPA 2009; WDEQ 2013), and one of these four wells with detectable levels of benzene exceeded these standards in 2013 with a concentration of 11.8 µg/L (Figure K-10I) (Trihydro 2014a). This exceedance has been attributed to a leaking reserve pit and the site has been entered into the WDEQ-administered Voluntary Remediation Program and is undergoing active remediation.

Toluene was detected in seven wells in the JIDPA in 2013 ranging from 0.44 to 38 µg/L (Figure K-10J). One sample outside of the JIDPA and NPL Project Area had a detectable concentration of toluene at 7.4 µg/L in 2013 (Trihydro 2014a). No wells with detectable levels of toluene exceed the EPA Primary Drinking Water Standard and Wyoming Groundwater Cleanup Level of 1,000 µg/L (EPA 2009; WDEQ 2013). There were no wells in the NPL Project Area with detectable levels of toluene in 2013. Ethylbenzene was detected in two wells in the JIDPA in 2013 with values of 0.3 and 3.2 µg/L, both of which are well below the EPA Primary Drinking Water Standard and Wyoming Groundwater Cleanup Level of 700 µg/L (Figure K-10K) (EPA 2009; Trihydro 2014a; WDEQ 2013). Xylenes were detected in four wells in the JIDPA in 2013, with values ranging from 0.85 to 35 µg/L (Figure K-10L) (Trihydro 2014a). None of the wells with detectable levels of total xylenes exceed the EPA Primary Drinking Water Standard and Wyoming Groundwater Cleanup Level of 10,000 µg/L (EPA 2009; WDEQ 2013). Ethylbenzene and xylenes were not detected in any of the wells in the NPL Project Area or outside of the NPL Project Area and JIDPA (Trihydro 2011, 2013, 2014a). In 2014, there were no wells in the NPL

Project Area or outside the NPL and Jonah Fields with detectable levels of benzene, toluene, ethylbenzene, or xylenes (Trihydro 2014b).

4.2.2.2.7. Methane

As indicated in Attachment C (*Water Quality Results from Water Wells in and Around the Project Area)*, dissolved methane levels were detected in water samples from five wells in the NPL Project Area and four wells in the area outside of the NPL Project Area and JIDPA in 2013. Methane was not analyzed in samples from JIDPA. The highest concentration detected in the NPL Project Area in 2013 was 5 mg/L (Figure K-8) (Trihydro 2014a). In 2014, 13 wells in the NPL Project Area and four wells outside of the NPL and Jonah Fields had detectable levels of methane (Trihydro 2014b). There are no drinking water or groundwater standards for methane; however, concentrations greater than 10 mg/L and less than 28 mg/L warrant investigation, and concentrations greater than 28 mg/L warrant immediate action due to risk of an explosion (Eltschlager et al. 2001). None of the detected concentrations of methane exceed these guidelines. Dissolved gas samples were collected from all wells and subjected to further isotopic analysis if the methane concentration exceeded 1.0 mg/L. Isotopic analysis of carbon and hydrogen in methane samples has been used to interpret the origin of methane gas to differentiate between biogenic gas, created by biological processes near or below the surface, and thermogenic gas, generally associated with thermal generation of oil and gas in the deep subsurface (Whiticar 1999). Over the four year sampling period (Trihydro 2011, 2013, 2014a, 2014b) methane was detected in 21 wells, and nine wells were at concentrations greater than 1.0 mg/L. All samples with concentrations greater than 0.1 mg/L are located in the eastern portion of the sampling area.

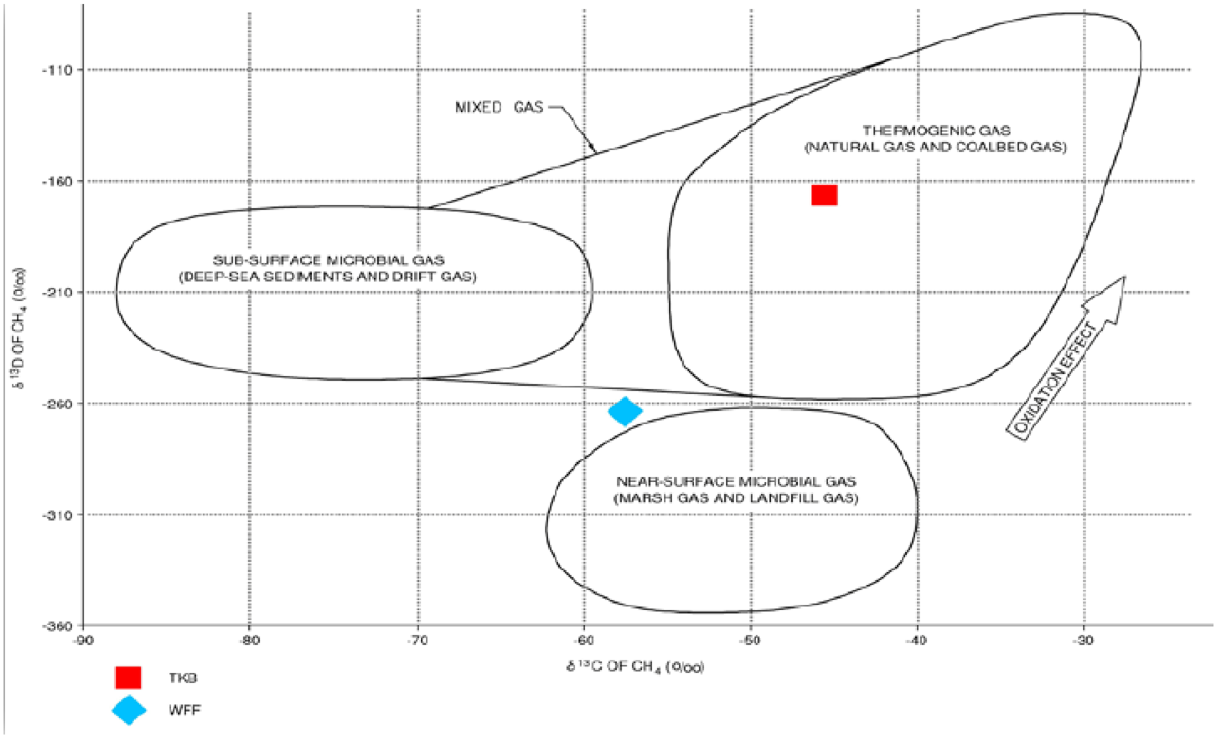
Eight methane samples from five wells (TKB, WFF, ETW, Err1, and Midland 2011-2) from the operator's sampling and analysis program were submitted for isotopic analysis between 2011 and 2014 to aid in determination of the source of the methane (Figures K-9, A-D) (Trihydro 2011, 2013, 2014a, 2014b). When plotted, samples from TKB and Err1 wells fell within the general range of thermogenic gas, and samples from Midland 2011-2, WFF, and ETW wells plotted near, but not within the biogenic near-surface region (Figures K-9, A-D). Trihydro (2011, 2014a, 2014b) interpreted the results of the methane analyses as potentially representative of methane from coal seams within the Wasatch; however, additional evidence has not been provided to support this interpretation. AMEC (2013b) found that the coal seams in the PAPA were not mature enough to generate a thermogenic hydrocarbon signature. In addition to Wasatch coal seams, the dissolved methane gas could be from a number of different sources including:

- Mixing of gases of different origins (e.g., microbial and thermogenic gas);
- Mixing of thermogenic gases with different maturities or complicated thermogenic histories; and,
- Microbial methane produced through biodegradation of hydrocarbon-containing compounds present in the Wasatch Formation, whether from natural or anthropogenic sources (AMEC 2013b).

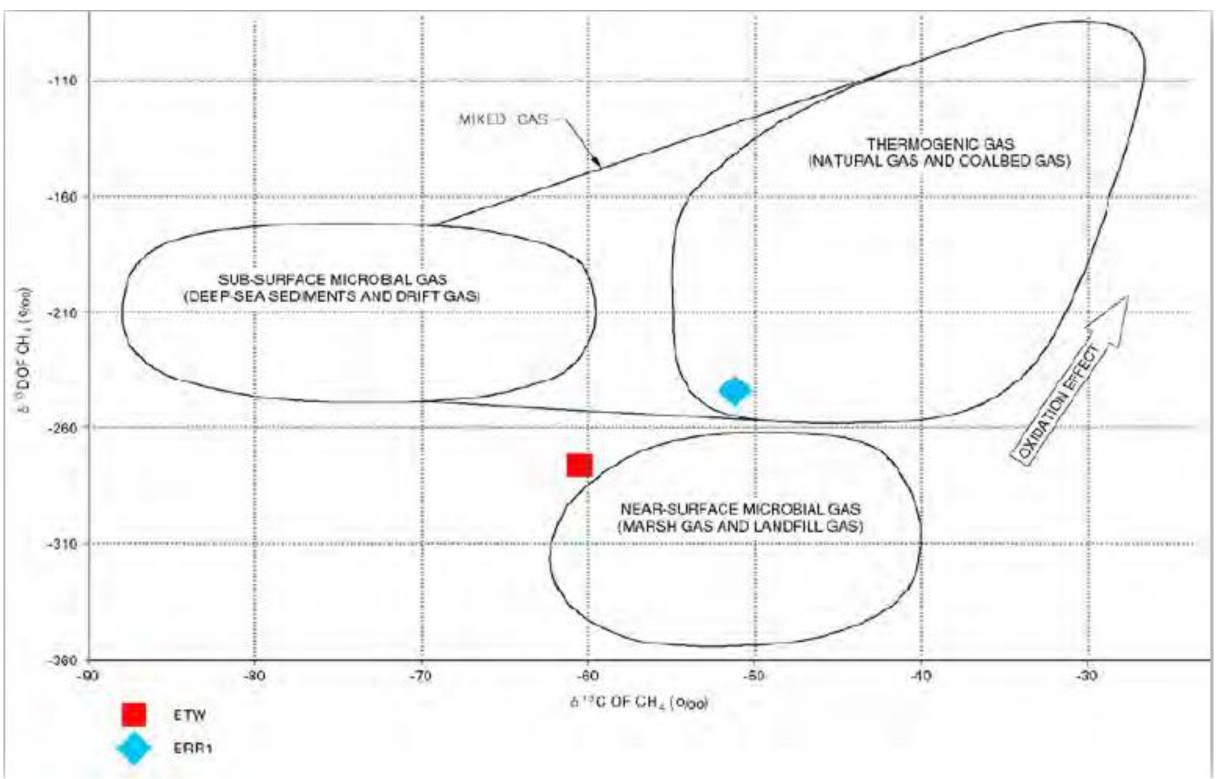
In 2016 and 2017, Jonah Energy compared results of production gas from the Project Area (Harris et al., 2013), to the dissolved methane found in NPL groundwater wells (field samples). The dissolved gas in groundwater did not match the production gas composition, concentration, or isotopic data; indicating that dissolved gas in groundwater was not production gas.

Figure K-9. Isotopic Analysis of Methane for Wells in the NPL Area, 2011-2014

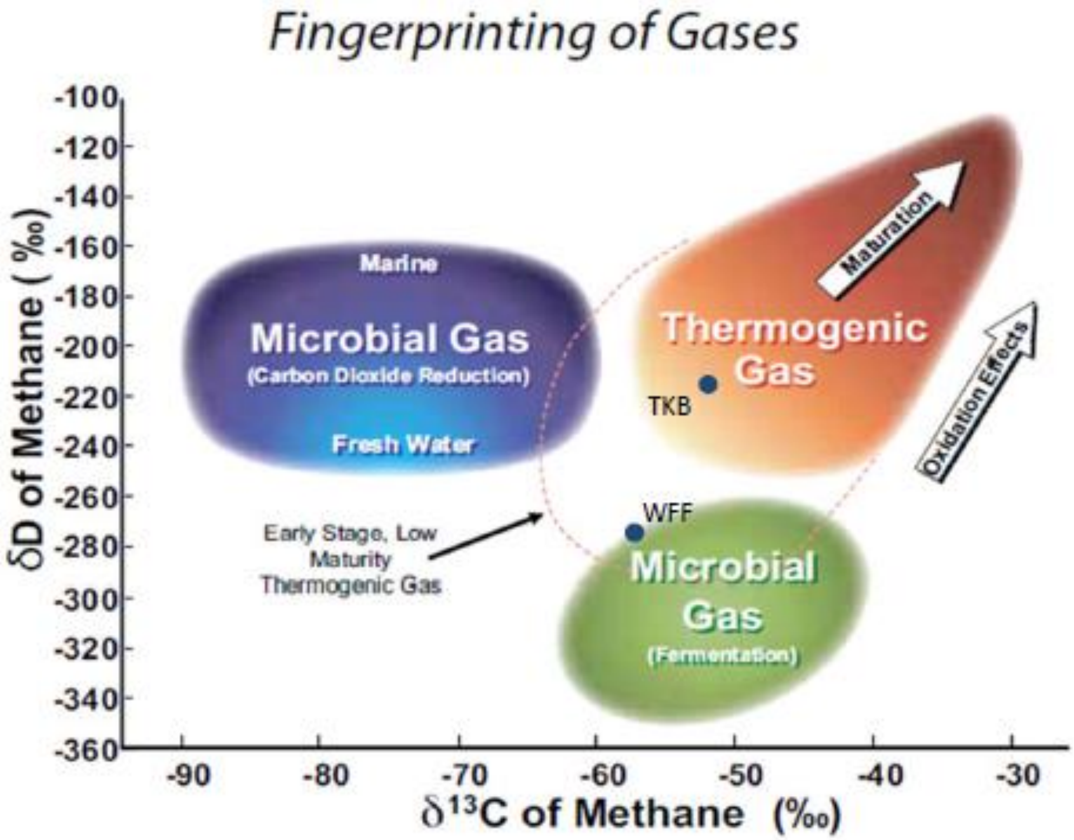
(A) Isotopic Analysis of Methane for TKB and WFF Wells, 2011



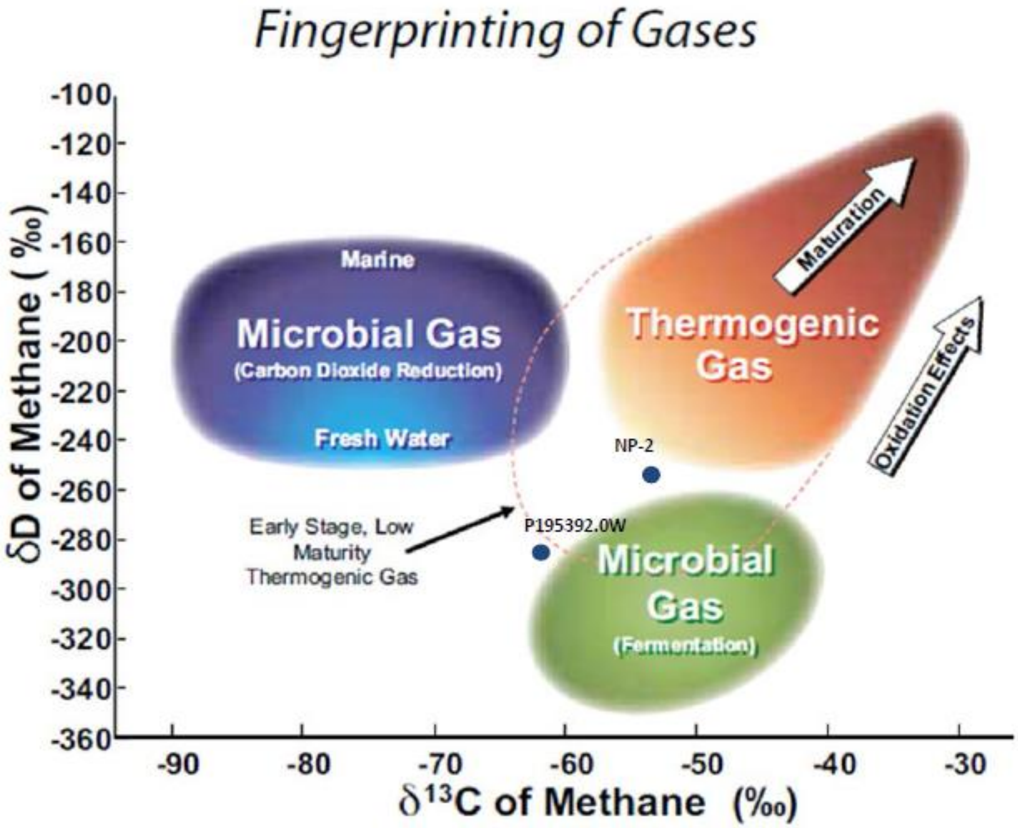
(B) Isotopic Analysis of ETW and ERR1 Wells, 2012



(C) Isotopic Analysis of TKB and WFF Wells, 2013



(D) Isotopic Analysis of Err1 and Midland 2011-2 Wells, 2014



Source: Trihydro 2011, 2013, 2014a, 2014b.

Notes for A and B: Chemical analysis based on standards accurate to within two percent. Analysis is of gas extracted from water by headspace equilibration. Analysis has been corrected for helium added to create headspace.

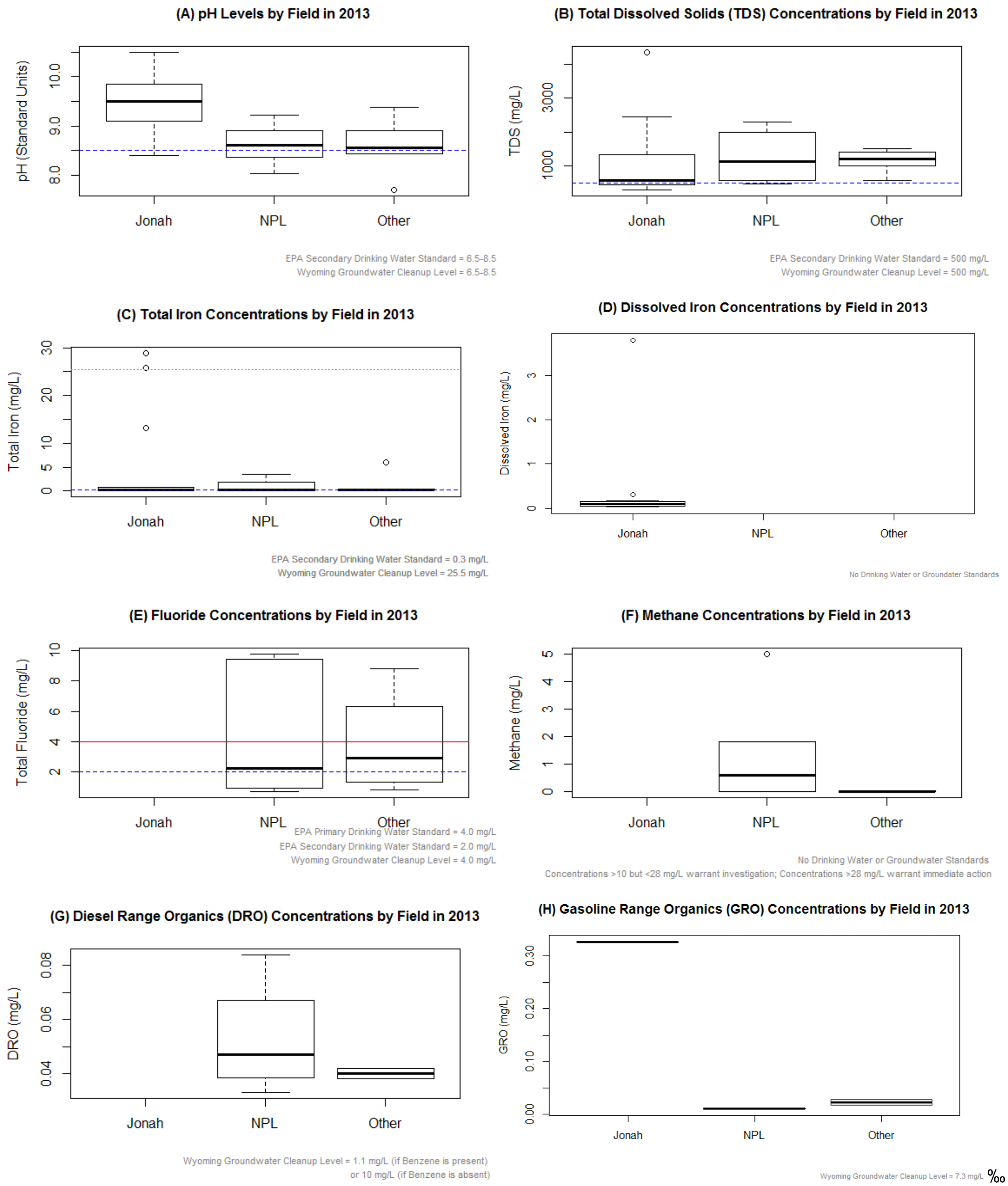
$\delta^{13}C_1$ = Carbon-13 isotope ratio, calculated from the following formula: $\delta C = [(^{13}C/^{12}C)_{SA}\text{-}(^{13}C\text{-}^{12}C)_{ST}/(^{13}C\text{-}^{12}C)_{ST}] \times 1000‰$
δDC_{SA} = Deuterium (H_2) isotope ratio, calculated from the following formula: $\delta S_{SA} = [(^{2}H/^{1}H)_{SA}\text{-}(^{2}H\text{-}^{1}H)_{ST}/(^{2}H/^{1}H)_{ST}] \times 1000‰$

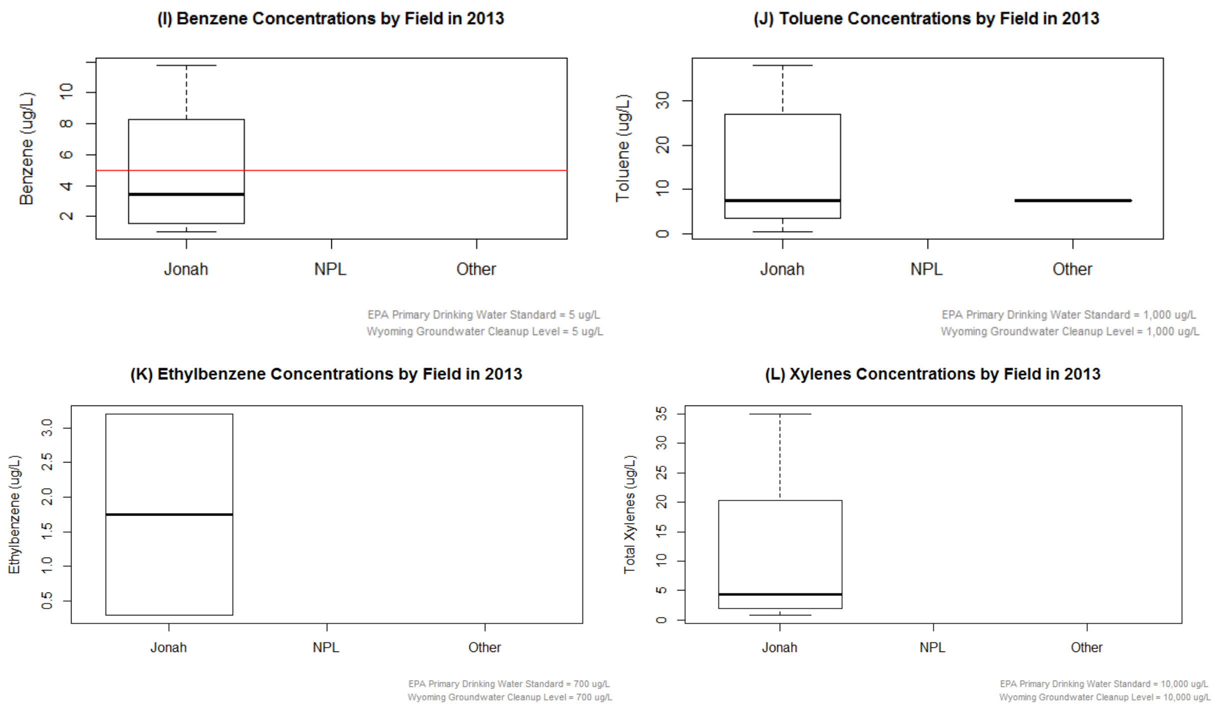
Notes for C: Dissolved Gas Identification $\delta^{13}C$ and δD from Isotech Laboratories, Inc. Chemical compositions are normalized to 100 percent. Mol. percentage is approximately equal to volume percentage. Analysis is of gas extracted from water by headspace equilibrium, corrected for helium to create headspace.

$\delta^{13}C$ = Carbon-13 isotope ratio; δD = Deuterium (H_2) isotope ratio
SA = Sample
ST = Internationally recognized standard

Gas groupings based on Coleman, 1995 (as cited in Trihydro 2011, 2013, 2014a, 2014b)

Figure K-10 (A-L). Boxplots of Water Quality Parameters for Water Supply Wells by Field in 2013





Sources: AMEC 2014; AECOM 2014; Eltschlager et al. 2001; EPA 2009; Trihydro 2014a; WDEQ 2013.

Red/solid line = EPA Primary Drinking Water Standard

Blue/dashed line = EPA Secondary Drinking Water Standard

Green/dotted line = Wyoming Groundwater Cleanup Level

mg/L milligrams per liter
µg/L micrograms per liter

Note: Some drinking water standards and cleanup levels are not show on the boxplots in cases where these limits are greater than the axis range of the plot. If two standards/limits are the same, the higher level is shown (e.g., if the EPA Primary Drinking Water Standard and the Wyoming Groundwater Cleanup Level are the same, the former is shown). Data were not available for parameters/fields missing boxplots. The methane concentration guidelines for action are established due to explosion risks, rather than health risks.

4.2.2.3. Fort Union Aquifer

In the GRB, water quality in the Fort Union Aquifer (the target zone for formation fluids injection) varies both laterally and vertically as a general function of transport distance from the recharge areas and subsurface depth (Bartos et al. 2010). Water quality data for the Fort Union Aquifer within the NPL Project Area are not available; however, data from several nearby JIDPA injection wells completed in the upper Fort Union were obtained from WOGCC (2014) and are summarized in Table K-6. Data from these wells represent the best available existing information for water quality in the Fort Union Aquifer. The chemical composition of the water is uniformly calcium chloride with some wells exhibiting high sodium concentrations. The sulfate and bicarbonate levels are very low compared to chloride. One well, on the southeastern side of the JIDPA, exhibited detectable concentrations of VOCs; however, no samples exceeded EPA (2009) MCLs for VOCs (Table K-6). Within the JIDPA, the porous sands in the upper Fort Union have consistently higher salinities than the underlying lower Fort Union, Lance, and overlying Wasatch Formations, as shown by a comparison of Tables K-4 and K-5, and in Attachment C (*Water Quality Results from Water Wells in and Around the Project Area)*. Jonah Energy has targeted these high salinity zones in the upper Fort Union as the proposed injection interval.

Table K-6. Water Quality Analysis from Selected Injection Wells in the JIDPA

Well Name	95-7 WDW SOL	3 WDW Jonah	14-21 WDW SHB	1 WDW Jonah	8-31 Cabrito*
Analysis Date	07/17/11	02/14/09	03/30/07	08/27/02	03/14/11
Injection Zone	Fort Union	Fort Union	Fort Union	Fort Union	Fort Union
Depth (ft. bgs)	4,898–7,160	5,705–6,400	5,200–6,515	6,004–6,513	5,944–7,720
Anions (mg/L)					
Chloride	**26,400**	**19,800**	**30,922**	**26,600**	**18,500**
Bicarbonate	60	18	0	39	254
Sulfate	**311**	**306**	15	116	106
Cations (mg/L)					
Sodium	3,970	3,190	3,650	2,516	3,270
Magnesium	80.0	15.0	59.0	33.0	30.3
Calcium	8700	8780	12700	12750	8020
Iron	7.47	15.00	7.00	0.20	0.35
Potassium	77.7	66.0	0.0	73.3	68.2
Lithium	0.29	NA	NA	ND	0.17
TDS (mg/L)	43,800	43,200	54,200	42,200	30,400
pH	6.51	6.57	7.57	7.27	7.71

Source: Data retrieved from WOGCC 2014.

Note: Exceedances of EPA (2009) Secondary Water Quality Criteria are indicated by bold numbers.

*Analysis from this well also noted Toluene (395 mg/L), Ethylbenzene (13.2 mg/L), and Xylenes (160 mg/L).

ft. bgs feet below ground surface
mg/L milligrams per liter

The EPA Secondary MCL for drinking water for TDS is 500 mg/L and chloride is 250 mg/L (EPA 2009) and WDEQ Class III water (suitable for livestock use) standard for TDS is 5,000 mg/L (WDEQ 2015). Data from JIDPA wells in the Fort Union Aquifer indicate TDS values from approximately 30,000 to 55,000 mg/L (Table K-6). Groundwater in the target injection zone has concentrations of TDS and chloride two orders of magnitude higher than drinking water standards for both parameters, and one order of magnitude higher than the Class III water standard, indicating that this is not a source of water for most applications. WDEQ groundwater regulations (2015) would likely classify the Fort Union minimally as either Class IV (B), which is water with TDS greater than 10,000 mg/L and suitable for industrial use, or more likely Class VI, which is unusable or unsuitable for use. The upper Fort Union proposed for injection does not contain usable water, as defined by the BLM, due to TDS content, and it does not meet the EPA definition of an USDW. Because of the high TDS content, injection into the upper Fort Union would not require an aquifer exemption from WOGCC (WOGCC 2014).

TDS concentration in the lower Fort Union is considerably lower than in the upper Fort Union. Water quality data from several injection wells in the Jonah Field completed in the lower Fort Union show less than 10,000 mg/L TDS. If the lower Fort Union is used for injection, it would require an aquifer exemption. Several injection wells in the Jonah Field use the lower Fort Union as the injection interval, and the EPA and WDEQ have determined that due to the combination of depth and water quality, this interval is not a source of drinking water and would qualify for an aquifer exemption (WOGCC 2014).

4.2.2.4. Mesaverde Aquifer

Water quality data for the Mesaverde aquifer was obtained from 74 produced water samples in the Green River Basin (Bartos et al. 2010). TDS concentrations range from 1,330 to 38,900 mg/L with a median concentration of 8,350 mg/L. In many samples TDS, chloride, sulfate and pH exceed aesthetic standards for domestic use. In the Project Area the Mesaverde aquifer is unlikely to be used as a source of drinking water due to its depth, quality, and availability of higher quality water at much shallower depths.

4.2.3 Groundwater Flow

The NPL Project Area is in the northwestern part of the GRB, and regional groundwater flows from the northern basin margins, where recharge occurs, southward to the center of the basin. Groundwater flow estimated from a potentiometric contour map of the lower Tertiary Aquifer (equivalent to the Wasatch Aquifer in the NPL Project Area) (USGS 2015a) indicates that groundwater flows mainly from the highlands of the Wind River Range, northeast of the analysis area, towards the west-southwest to the Green River (Figure K-11). Based on regional flow patterns, it is likely that a portion of groundwater flows through the PAPA and JIDPA before entering the NPL Project Area. There is also a component of flow directed towards the Big Sandy River to the southeast. Locally within the NPL Project Area, the direction of groundwater flow may differ from regional flow due to the heterogeneity of the rocks and the fluvial nature of the channel sand deposits within the Wasatch and Fort Union Aquifers. The potentiometric map (Figure K-11) and groundwater flow presented in this section represent the best available existing information as no NPL Project Area specific groundwater flow data have been collected at the time of this report.

Figure K-11. Potentiometric Surface of the Lower Tertiary Aquifer System (including the NPL Project Area)

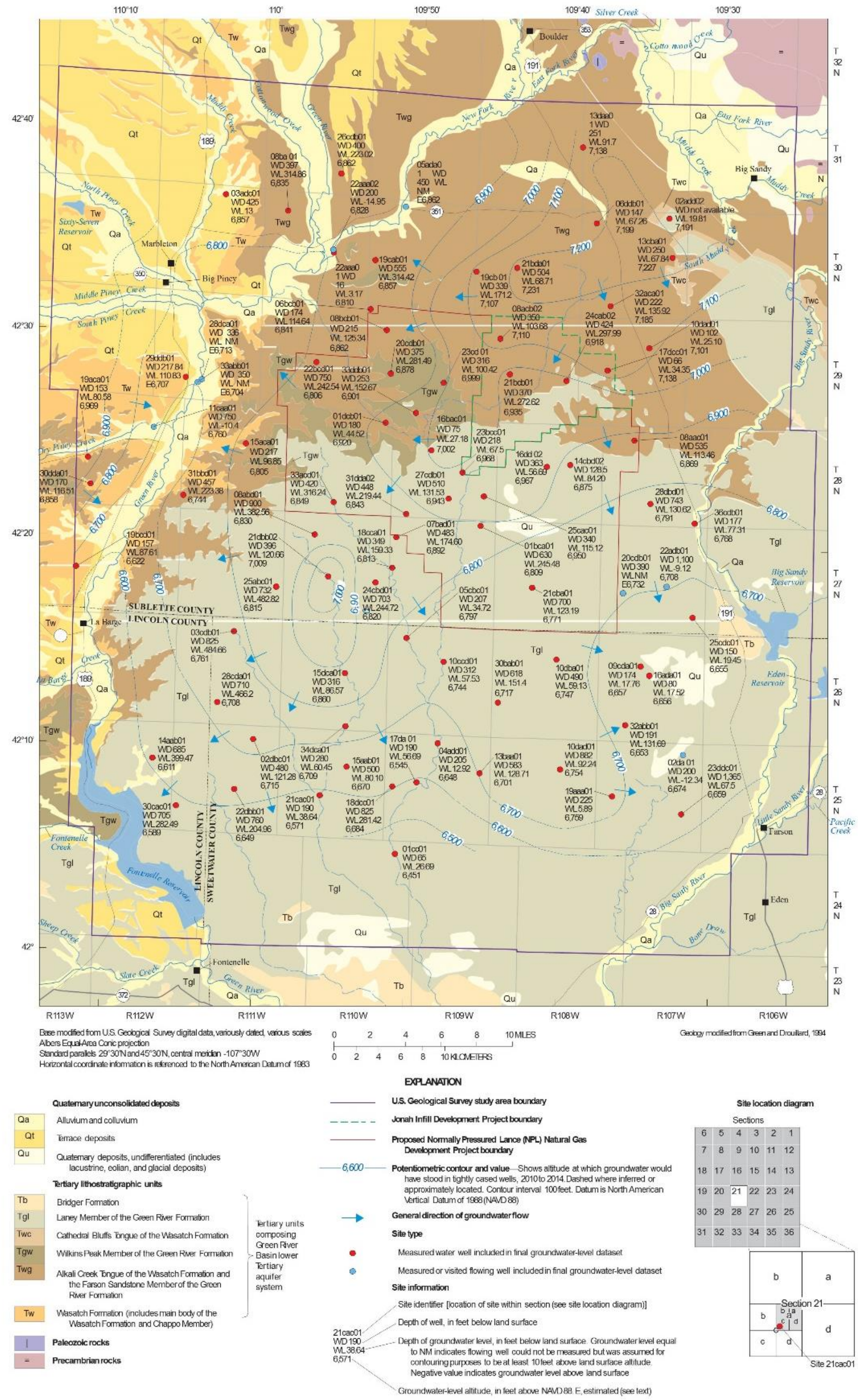


Figure 10. Generalized potentiometric surface of the Green River Basin lower Tertiary aquifer system, 2010–14, northern Green River structural basin, Wyoming.

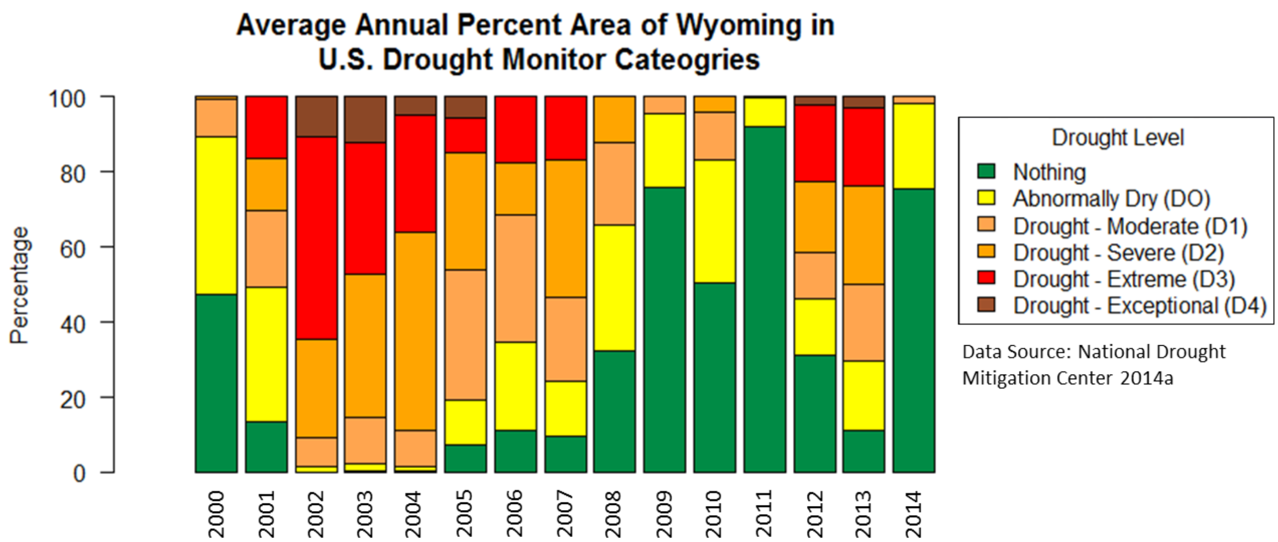
4.2.4 Depth to Groundwater

Groundwater is typically under confined (artesian) conditions in the GRB and, although groundwater may occur at great depth, the potentiometric surface of the water under pressure is often near ground surface. In the shallow aquifer and where the saturated Tertiary aquifer beds occur at shallow depth, groundwater may be unconfined (Bartos and Hallberg 2010). In general, the groundwater depths in both confined and unconfined wells in the GRB are within 200 feet of ground surface (Bartos and Hallberg 2010). Depth to groundwater maps prepared in support of the Wyoming Groundwater Vulnerability Mapping project (Hamerlinck and Arneson 1998) show that groundwater is typically between 50 and 100 feet below surface in the northwest part of the NPL Project Area and between 100 and 200 feet below surface in most of the remaining portions of the NPL Project Area. One significant deviation from the trend is the western Tea Kettle Butte area in the east-central portion of the NPL Project Area, where sandy surface soils are present and water levels are between 10 and 50 feet below surface (Figure K-1). Water level data were generally not collected from stock wells during the Trihydro (2011, 2013, 2014a, 2014b) annual sampling program because the sampling locations were not constructed to allow access. In cooperation with the BLM, the USGS collected water level measurements in the Project Area between 2010 and 2014 (USGS 2015a) from wells determined to be suitable for monitoring water level (USGS 2013). In the suitable wells, depth to water in the Laney Aquifer ranged from 26.29 feet e to 149.11 feet below land surface. For wells completed in the Wasatch (including the Green River equivalent strata), water levels ranged from 0 (seven flowing wells) to 484.66 feet below land surface. The 2013 USGS inventory of wells indicated that the shallowest depth to water in the Laney is in Townships 25N and 26N, Range 107W, southeast of the NPL Project Area, where the depth to water is less than 20 feet. Within the NPL Project Area where the Laney is targeted for water use, water levels range from 77.31 to 97.76 feet below ground surface. Flowing wells completed in the Wasatch are generally located in the eastern portion of the analysis area (Figure K-2), but several flowing wells were noted by USGS (2015) in the Green River floodplain in Townships 28N and 29N, Ranges 111W and 112W. North of the NPL Project Area flowing wells were identified in the New Fork River floodplain. The greatest depth to water in wells completed within the Wasatch Formation occurs south and west of the NPL Project Area where depth to water exceeds 450 feet below surface. USGS noted that some wells were pumping upon arrival or had recently been pumped, so the depths reported may be greater than static water level. In the far western part of the analysis area near Big Piney, groundwater discharges to the Green River and the depth to groundwater is very shallow, commonly less than 10 feet, and exhibits an upward gradient (Jorgensen 1994).

Water levels are not measured in the operating water supply wells at Jonah because the wells are not constructed to allow water level measurements (AMEC 2014). One JIDPA water supply well, Corona 2-14 (Map Reference #61 on Figure K-8), was shut down in 2006 as a result of contamination detected during regular sampling. Since 2009 water levels have been measured and observed to have increased from 290.78 feet below ground to 275.38 feet below surface; a recovery of 15.4 feet in five years.

Changes in groundwater levels are typically seasonal, although their effects can be exacerbated during drought conditions. During the drought of 1999-2007, groundwater levels across Wyoming decreased anywhere from a few feet to tens of feet (WSGS 2010). Figure K-12 shows the average annual percent of area for the state of Wyoming that falls within each of the drought monitoring categories in the U.S. Drought Monitor Classification Scheme (National Drought Mitigation Center 2014a). These categories are based on indicators and local reports from expert observers and range from "Nothing" (i.e., normal conditions) to "Drought – Exceptional" (i.e., exceptional and widespread drought conditions and impacts with shortages of water creating water emergencies) (National Drought Mitigation Center 2014b). The drought became more widespread and severe from 2000 (data were not available for 1999, which was the beginning of the drought) until 2008, when levels no longer reached “Extreme” conditions. In 2012 and 2013, significant areas of Wyoming again reached severe and exceptional drought conditions. The data for 2014 (currently available through May) shows no areas of Wyoming in drought conditions above “Moderate” (National Drought Mitigation Center 2014b).

Figure K-12. Average Annual Percent Area of Wyoming in U.S. Drought Monitor Categories



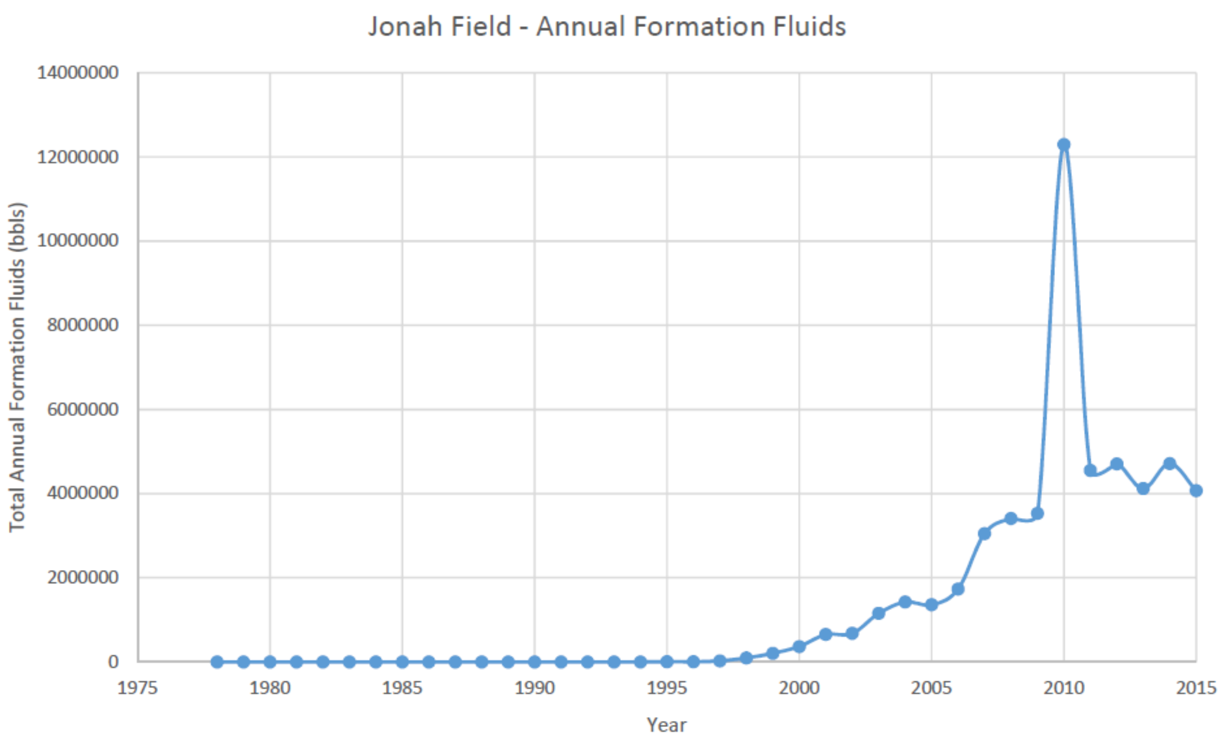
Groundwater levels can change over time in response to long-term weather patterns and water use. Historic depth to water measurements made in existing wells can be compared to recent water levels in the same wells to identify changes over time. USGS (2015) evaluated data from 27 wells in 2012-2014, mostly in the southern part of the study area, in which previous measurements had been taken in the 1960s and 1970s. The differences in water levels ranged from an increase of 5.5 feet to a decrease of 86.9 feet. Seventy-four percent of the wells showed a decrease in groundwater levels with declines ranging from 0.1 to 86.9 feet.

4.2.5 Formation Fluids

During operation, gas wells produce water along with natural gas and petroleum liquids. The water is brought to the surface, separated from the gas and other liquids and is either beneficially reused or disposed of in permitted surface locations or injected into subsurface locations. Formation fluids coming from the Lance Formation in the JIDPA are re-injected into the Fort Union, as described above, or piped or trucked to a central recycling facility to be reused for drilling and other field operations. Figure K-13 depicts annual formation fluids volumes for the JIDPA for 1978-November 2015. There were no formation fluids reported from 1978, the first year Jonah wells began producing gas, to 1984, and in 1985, 63 bbls of water were produced. An average of 1,372,373 bbls of water has been produced each year since 1978, and formation fluids spiked in 2010 at 12,298,414 bbls. Most recent data (through November 2015) indicate that the Jonah wells have cumulatively produced 52,150,184 barrels (approximately 6,722 acre-feet) of formation fluids (Table K-7) (WOGCC 2014).

Gas wells within the NPL Project Area (not designated as within the JIDPA) have cumulatively produced an estimated 217,186 barrels (28 acre-feet) of water from 1997 through April 2014; more current data were not available at the time of this report) (Table K-7) (WOGCC 2014). These values are estimates as some wells within the NPL Project Area are categorized by WOGCC as being within the JIDPA; therefore the field statistics for Jonah include some NPL Project Area wells, and as a result, formation fluids volumes for the JIDPA are likely lower than shown, and the NPL Project Area values are likely higher than shown (Figure K-8). In general, over time, gas wells tend to produce more water, and some wells are shut in or abandoned if water production is excessive. USGS found that gas-water ratios from the Jonah and Pinedale Fields do not change over time (Nelson et al. 2010). The reservoir characteristics in the NPL area have not been evaluated, and there is uncertainty as to whether the gas-water ratios will remain the same over time, like nearby structurally controlled fields, or if they will decrease over time.

Figure K-13. Total Annual Formation Fluids for the Jonah Field, 1978-2015



Source: WOGCC 2014.

bbl barrels

Note: 2015 data only include data for January through November. December data were not available at the time of this report.

Table K-7. Total Estimated Formation Fluids from Existing Oil and Gas Wells in the Jonah Field and NPL Project Area

Field/Area	Total Formation Fluids Volume (bbls)
Jonah Field[1]	52,150,184
NPL Project Area[2]	217,186

Source: WOGCC 2014.

[1]Total volume includes all formation fluids from 1978 through November 2015.
[2]Total volume includes all formation fluids from 1997 through April 2014.

bbls barrels

4.2.6 Groundwater Use

Wyoming State Engineers Office (SEO)[2] permits (Wyoming SEO 2014), USGS data (USGS 2013), and well sampling reports by Trihydro (2011, 2013, 2014a, 2014b) were used to develop a comprehensive list of water wells and groundwater uses within the NPL Project Area. Attachment B (*Water Supply Wells in and around the NPL Project Area*) identifies water supply wells and their uses, and Figure K-2 depicts the location of existing water supply wells. SEO data provides the most comprehensive information on well location and use, although several wells identified by USGS were not in the SEO database, and USGS data did not specify designated uses. The water rights search was conducted in July 2014 and included all groundwater permits categorized as complete, incomplete, blank, and fully adjudicated. Permits listed as abandoned, expired, or cancelled, were not included in the search. For wells where the use was not specified, it was assumed the well was used for livestock watering (stock use) as this is the primary permitted use for water supply wells in the analysis area. Based on available data, there are 32 stock water wells and no domestic water supply wells within the NPL Project Area. SEO records do not report any irrigation, industrial, or municipal wells within the NPL Project Area. Five wells were identified in the NPL Project Area as miscellaneous (MISC) use and are used for oil and gas operations by the JIDPA; however, only two wells, Holmes Federal 5-1 and Jonah Workforce Facility, operated in 2013. The volume of water used from the Holmes Federal 5-1 is not reported in the SEO database or by Jonah Energy (the operator) to the BLM. It is assumed that the well uses the average amount calculated for JIDPA supply wells, 235,591 barrels/year (30.4 acre-feet). In 2013 the Jonah Workforce Facility well withdrew 128,800 barrels (16.6 acre-feet) of water (Encana 2014).

The primary aquifer for many of the stock wells was identified by USGS, but for some wells and springs the aquifer was not identified. For wells without an identified aquifer, an aquifer was assigned based on the best available data from local geological features, well depths and descriptions, and comparisons to nearby wells. Most of the wells appear to produce water from the Wasatch Aquifer; however, at least four wells produce water from the Laney and one produces water from an alluvial aquifer.

Historic water withdrawal records were not available for stock wells in the NPL Project Area, therefore an estimate of water use was developed using the methods and default use values outlined in the PAPA Numerical Groundwater Model (AMEC 2013a). According to AMEC (2013a), who reported results from Clarey et al. (2010), the average annual groundwater volume used for each stock well in the GRB is 0.6 acre-feet/year. Multiplying this by the number of stock wells identified in the NPL Project Area (32) results in 19.2 acre-feet/year of groundwater use. No wells were identified as domestic supply wells in the NPL Project Area; however, if any are present, each would be assumed to supply one household, with an average of 2.47 persons per household (as cited in AMEC 2013a). Assuming an average use of 75 gallons per person per day (as cited in AMEC 2013a) and converting gallons to acre-feet/year, it is estimated that 0.21 acre-feet/year would be withdrawn for each domestic well. The PAPA analysis assumes that only 10 percent of the domestic water withdrawn is consumed and 90 percent is returned; therefore, the consumptive use of groundwater for domestic purposes is estimated at 0.021 acre-feet/year per well. Based on these estimates, total annual groundwater use within the NPL Project Area is estimated at 513,353 barrels (66.2 acre-feet) per year (Table K-8).

The nearest municipal water well is located in Big Piney, approximately eight miles northwest of the NPL Project Area. The municipal water well in Big Piney draws from alluvial sediments in the Green River

[2] *SEO records are updated regularly, and permitting information included at the time of this report is based on current information.*

floodplain and is not likely to be influenced by any activities in the NPL Project Area due to the distance from the NPL Project Area and the water source (alluvial sediments in Green River floodplain).

Table K-8. Annual Groundwater Use Estimates within the NPL Project Area

Water Use	Volume (barrels)	Volume (acre-feet)
Stock	148,962	19.2
Domestic	0	0
Miscellaneous (oil and gas operations)	364,391	47.0
Total	**513,353**	**66.2**

Source: AMEC 2013a and methods described in text above.

General consumptive water use in the Upper Green River Basin primarily includes irrigation and stock watering, with irrigation water being mostly obtained from surface water diversions (WWDC 2014). There are seven irrigation wells in the Green River Basin (WWDC 2014), although well data reveal no irrigation wells are within the Project Area (see Attachment B a full list of wells in the Project Area).

Groundwater use in the JIDPA is tracked and recorded in accordance with the requirements of the JIDPA ROD (BLM 2006c). In 2013, Jonah Energy and Linn Energy reported 20 wells in the JIDPA withdrew a total of 607.3 acre feet of water (Encana 2014; Linn Energy 2014). These wells range in depth from 575 to 1,100 feet below ground surface and obtain water from the Wasatch Aquifer. The amount of water used for drilling and completion in 2013 is likely less than average water use for the JIDPA drilling program. BLM records indicate that between 2008 and 2014, operators drilled and completed between 52 and 155 gas wells per year, with an average of 102 gas wells per year (BLM 2015b). In 2013, 69 gas wells were drilled and completed, approximately 30 percent less than the average number of gas wells drilled since 2008.

4.2.7 Sources of Groundwater Recharge and Discharge

Groundwater recharge is the amount of water falling as precipitation that percolates into and through the soil and underlying rock to eventually migrate into and recharge water in the aquifer. Recharge is generally determined by the amount of precipitation, permeability of the surface and subsurface formations, the vertical hydraulic conductivity, the depth of the aquifer, and the access of the aquifer to surface infiltration (i.e., if there is a confining layer between the ground surface and the aquifer). Also, evaporation at the ground surface in dry climates and surface vegetation uptake (transpiration) can remove water from soils, resulting in low or negative recharge rates. In the analysis area, recharge rates range from five inches per year to negative values due to low precipitation and high evapotranspiration (Clarey and Copeland 2010; WWC Engineering et al. 2010). The Tea Kettle Butte area in the east-central portion of the NPL Project Area shows a positive recharge value of less than one inch per year. This is due to the permeable surface soils in the area (Hamerlinck and Arneson 1998)).

The Laney Member of the Green River Formation has a gradational contact within the upper part of the Wasatch Formation, and groundwater moving south in the Wasatch freely moves across the boundary and may be a source of recharge for the Laney Aquifer in the southern portion of the NPL Project Area (Martin 1996). A minor amount of discharge from the Laney may occur from wells and springs whose source is the Laney, but most discharge is to the Big Sandy and Green Rivers south of the NPL Project Area (Bartos and Hallberg 2010).

The primary source of recharge to the Wasatch Aquifer is from areas on the flanks of the aquifer, in particular the foothills of the Wind River Range to the northeast and the Wyoming Range to the northwest of the NPL Project Area, which receives snowmelt and precipitation from the mountains (HydroGeo 2004) (Figure K-14). The greatest amount of discharge from the lower Tertiary aquifer system, including the Wasatch and Fort Union Aquifers, is to the Green and New Fork Rivers upstream of Fontenelle Reservoir, which is west-southwest of the Project Area (Figure K-14) (Clarey and Copeland 2010). As indicated in Figure K-14, net recharge is near zero throughout most of the NPL Project Area and recharge is not expected to provide significant input to the aquifer. However, the permeable area near Tea Kettle Butte comprises approximately 5.7 square miles, and assuming one percent[3] of the recharge reaches the aquifer, the Wasatch receives approximately 27 acre-feet of recharge per year.

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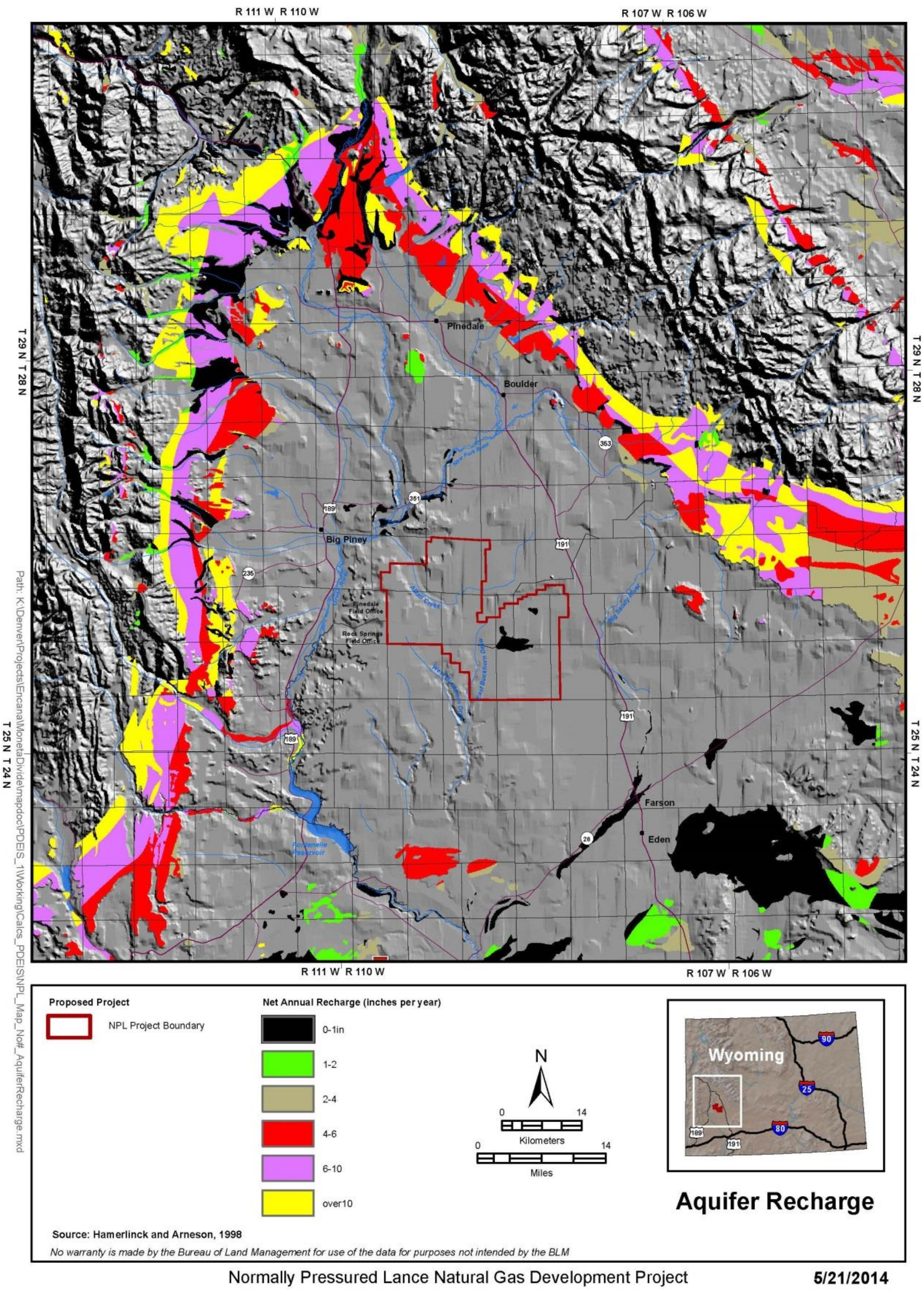
[3] *The assumption of one percent infiltration comes from Wyoming State Geological Survey Green River Basin Water Plan II Groundwater Study Level 1 (2007–2009) (WSGS 2010).*

Figure K-14. Net Annual Recharge in and around the NPL Project Area



4.2.8 Aquifer Sensitivity

The sensitivity of aquifers to contamination from surficial sources is influenced by precipitation, the permeability of surficial materials, and depth to groundwater. Aquifer sensitivity in the GRB was evaluated by Clarey and Copeland (2010) based on initial models for Wyoming developed by Hamerlinck and Arneson (1998) and is depicted on Figure K-15. The majority of the NPL Project Area is mapped as being not highly sensitive to contamination at the surface, primarily due to low precipitation and depth to groundwater. The surficial alluvial aquifer mapped in the Tea Kettle Butte watershed is relatively highly sensitive to contamination at the surface. The aquifer sensitivity is high west and northeast of the NPL Project Area near the Green and Big Sandy Rivers, where the aquifers are shallower and sand and gravel alluvium are at the surface.

WDEQ, in association with the USGS and the University of Wyoming, conducted aquifer monitoring prioritization to collect groundwater quality information in shallow aquifers and rank aquifers most susceptible to water quality degradation from human activities (Bedessem et al. 2005). The ranking of priority aquifers combined aquifer sensitivity mapping from a previous study on aquifer vulnerability to pesticides, groundwater well density data from SEO records, land use, and known and potential sources of contamination derived from land use and contaminated site data sources. WDEQ identified 33 priority areas for monitoring in six geologic basins including two areas within the GRB near Pinedale and Big Piney. Within the NPL Project Area and the JIDPA, no aquifers were delineated as high priority for groundwater monitoring (Figure K-16). The nearest high priority aquifers for monitoring are within the Green River Valley near Big Piney and the northern portion of the PAPA. Both areas are approximately six miles from the NPL Project Area.

To assist with the identification and mitigation of point source pollution related to activities from oil and gas development, the BLM Pinedale Field Office Approved Resource Management Plan and ROD (BLM 2008) includes a management action to establish a groundwater monitoring program in areas designated as high and moderately high priority by WDEQ.

Figure K-15. Aquifer Sensitivity Map

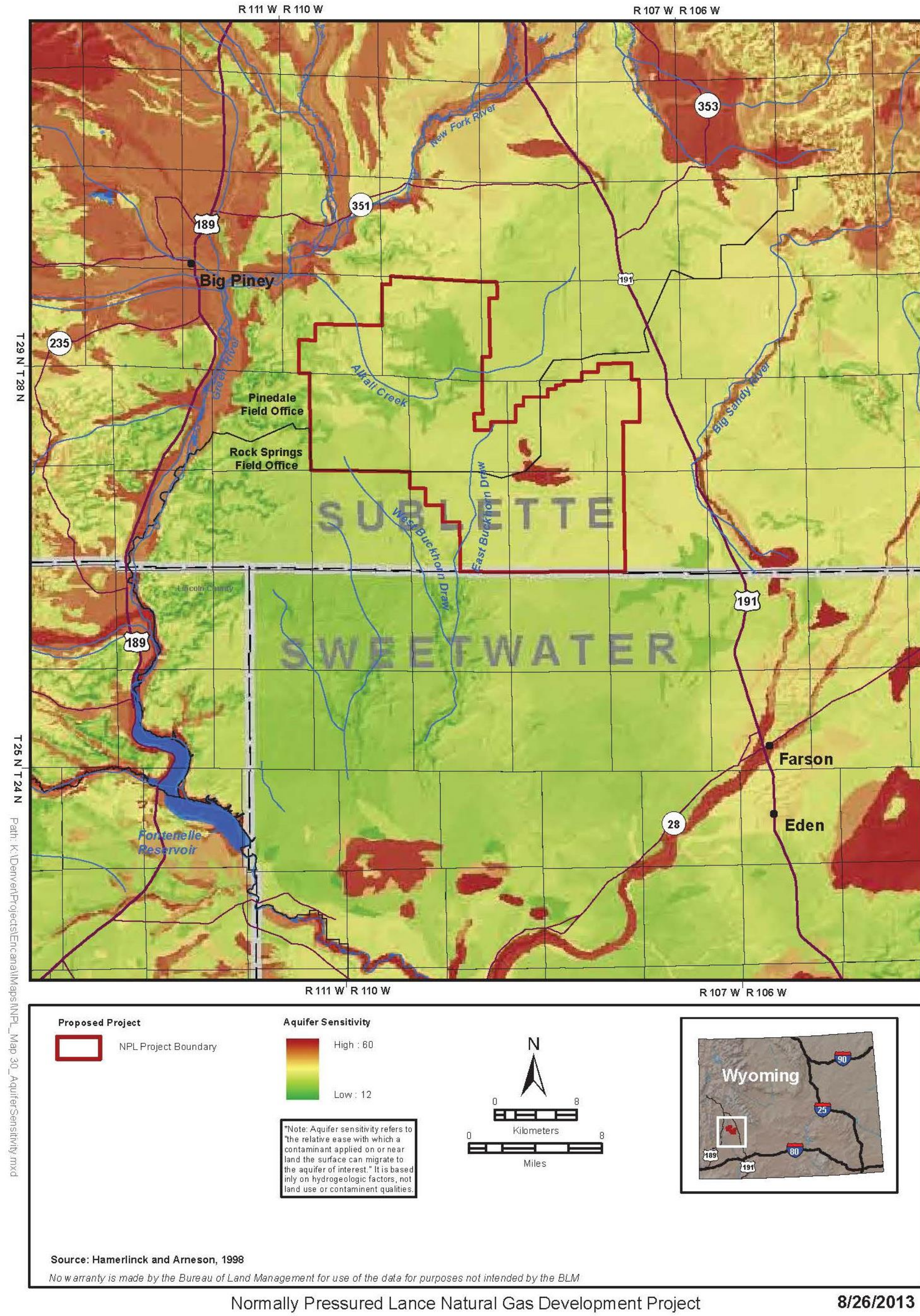
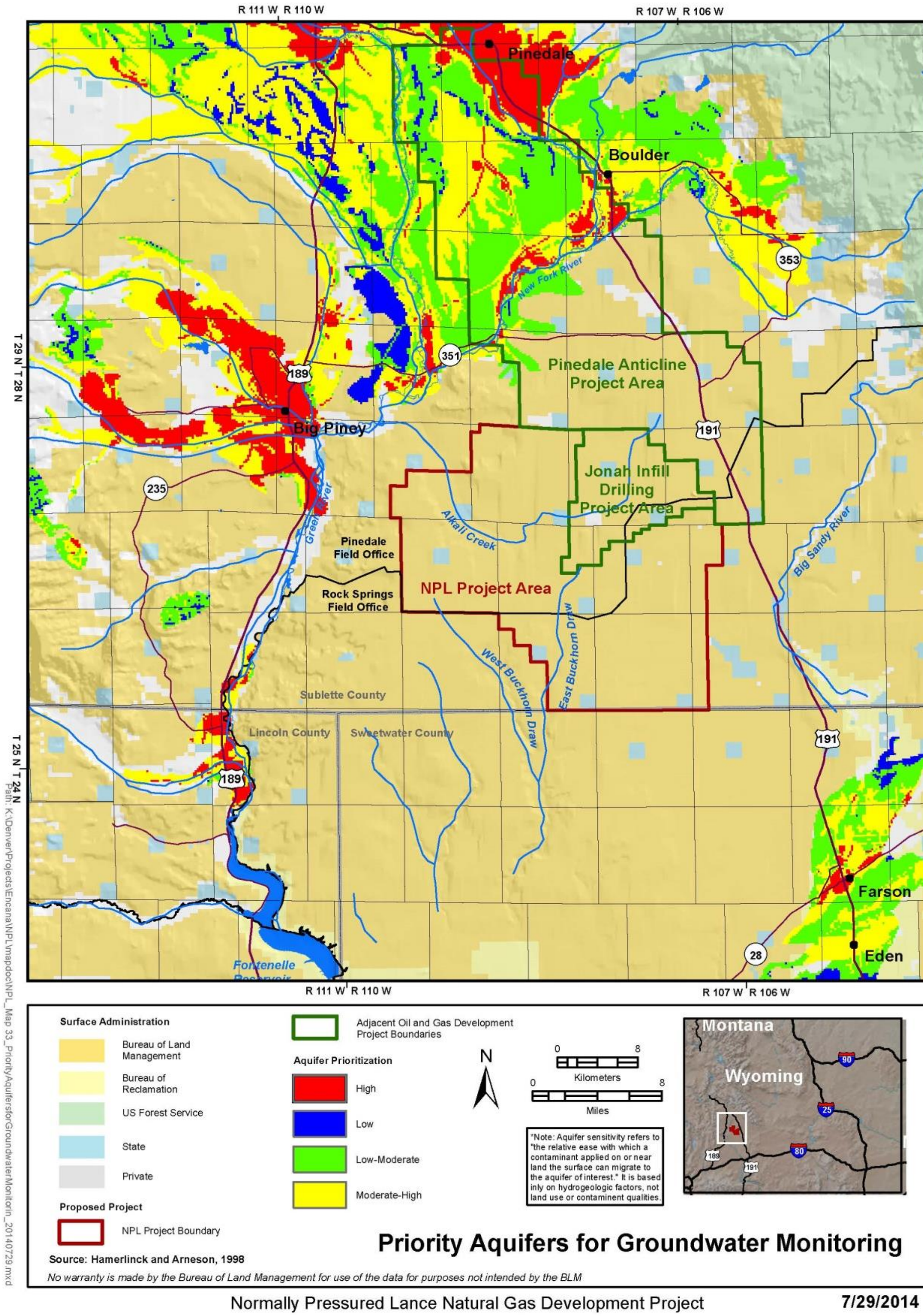


Figure K-16. Priority Aquifers for Groundwater Monitoring



5.0 POTENTIAL IMPACTS

5.1 Surface Water Impacts

The Proposed Action would result in surface disturbance in the NPL Project Area due to construction of well pads, regional gathering facilities, roads, and other infrastructure. The disturbance has the potential to decrease infiltration of precipitation, alter surface water runoff drainage, and increase erosion. Potential impacts to surface water quality resulting from the Proposed Action would include accidental discharge (spill) of completion fluids, drilling fluids, and formation fluids; and, on and off-site degradation of surface water quality from sedimentation, turbidity and salinity. The results of the AGWA modeling (BLM 2013a) for the NPL Project indicate there is a low probability of transporting sediment and salt from contributing watersheds to major stream channels.

All drainages in the NPL Project Area are ephemeral and intermittent, which do not hold surface water year-round, and most streams only flow following snowmelt and precipitation events (WWDC 2014). However, potential indirect impacts from project development could occur to the upper Green and Big Sandy Rivers and their tributaries, both within the NPL Project Area, and potentially outside of the NPL Project Area boundary in the form of increased surface runoff, sediment transport, erosion, and salinity from areas disturbed within the NPL Project Area. Four springs are known to exist in the area; two unnamed springs are within the NPL Project Area boundary, while North Sublette Meadow Spring and Juel Spring are immediately east of the NPL Project Area (Figure K-1). None of the springs are known to produce perennial surface flows that reach other surface waters, and none of the reservoirs contain permanent water (BLM 2013a).

AGWA was chosen for the hydrologic analysis of the NPL Project because it was designed to assess the trends and magnitudes of hydrologic changes associated with surface disturbance activities, such as oil and gas development, especially in regions with limited runoff and climate data. Additionally, AGWA can identify areas that are susceptible to changes in land cover, surface-disturbing activities, and/or climate. Areas within the analysis area susceptible to land-use changes from the Proposed Action and alternatives were identified using the AGWA tool with the goal of comparing and predicting surface runoff, water yield, and sediment yield for the following scenarios:

- Pre-development: a representation of the landscape prior to significant natural gas development in the NPL Project Area and vicinity, particularly the JIDPA;
- Present: a representation of existing conditions within the NPL Project Area and the JIDPA, including wells pads, access roads, and pipelines;
- Two-Mile Buffer (Proposed Action): a reasonable representation of Jonah Energy's Proposed Action using Jonah Energy's placement of proposed power lines and Regional Gathering Facilities (RGF); and
- Worst Case: represented by locating proposed natural gas wells in areas identified in the pre-development scenario as having the highest potential for increased surface runoff.

The results of the *AGWA Technical Report* (Appendix J) indicate there is a low probability of transporting sediment and salt from contributing watersheds to major stream channels for all scenarios modeled. However, heavy storms may increase the probability of impacts to tributaries of the Green and Big Sandy Rivers, as well as the rivers themselves, especially in watersheds where development may be concentrated and sediment transport more likely. The water quality of runoff from ephemeral streams and washes is largely dependent upon the amount of salts, sediments, and organic materials that accumulate in dry stream channels between runoff events. The degree to which these materials build up between runoff events is influenced seasonally by physical characteristics and land uses occurring within the watershed.

The Proposed Action would not directly impact the functioning condition of streams or rivers in the analysis area through the direct alteration of hydrologic, vegetative or depositional characteristics. However, indirect impacts on the functioning conditions of the Big Sandy River, Green River and Alkali Creek could result from increased surface runoff and erosion in the NPL Project Area if sediment is transported to these surface waters from the NPL Project Area. The potential for impacts to the functioning conditions of these surface waters would be greatest within segments evaluated as functioning at-risk for degradation, including segments of Alkali Creek downstream of the Project Area, and segments of the Big Sandy River, located adjacent to the Project Area.

Sediment would be transported incrementally downstream from the Project Area over time by a sequence of precipitation events and sequential flows. As a result, the likelihood for the Proposed Action to contribute to a downward trend in PFC for the Green River and Big Sandy River is low. However, the potential for the Proposed Action to contribute to the degradation of Alkali Creek is greater due to the presence of functioning at-risk for degradation segments near the NPL Project Area. The Proposed Action may increase channelization and discharge velocities along portions of Alkali Creek within the Project Area, which may also impact riparian and/or adjoining wetland habitats and increase the rate of sedimentation in downstream segments of Alkali Creek in the analysis area.

5.2 Groundwater Use Impacts

In 2013, Encana and Linn Energy reported using 4,711,821 barrels (607 acre-feet) of water for oil and gas operations within the JIDPA from 21 water supply wells, all but one of which are within the JIDPA (AECOM 2014; Encana 2014). As a result of fewer wells drilled in 2013, the amount of water used is likely lower than the average amount of water expected to be used in future years. The Proposed Action would require an estimated 35,000 bbls of water for drilling and completions of each well. Approximately 71 percent of water (25,000 bbls per well) for drilling and completion would be obtained from recycled sources (e.g., JIDPA Water Treatment Facility) with the remaining 29 percent of water (10,000 bbls per well) coming from shallow groundwater wells in the top 1,000 feet of the Wasatch Formation. No water would be removed from the Fort Union Aquifer due to its poor water quality and great depth. During the development phase, the Proposed Action would also require an estimated 13,620 bbls of groundwater per year for new road construction dust control, an average of 74,910 bbls of groundwater per year for road maintenance dust control, and 63,000 bbls of groundwater per year for well pad construction dust control. Total groundwater withdrawal for use development of the NPL Project Proposed Action is estimated at 474.0 acre-feet per year during the 10-year development phase (EnCana 2014). Total groundwater withdrawal during production for the NPL Project Proposed Action is estimated at 17.6 acre-feet per year during the approximate 30-year full production phase for road maintenance and dust control (years 10 to 40).

Fresh water would be obtained from existing shallow water wells in the JIDPA and NPL Project Area and would be used for drilling, cement production, and casing surface aquifers. If needed, new wells may be drilled at appropriate locations in the NPL Project Area to service new development activities. The primary factor driving the need for new water supply wells would be the distance from existing water supply wells to new development locations. As new development areas are located further from existing water supply wells, the need for new water supply wells closer to development areas would increase. The new water supply wells could be located at the RGF locations servicing well clusters. The increased potential for new water supply wells in the NPL Project Area would occur at a similar timeframe as the decline in water supply needs in the JIDPA. As a result, the total water withdrawal from the near-surface aquifers would remain relatively constant as NPL Project development and water use increases and JIDPA development and water use decreases.

To ensure that usable water is protected all water supply wells will be constructed and operated in accordance with SEO regulations (Wyoming SEO 2011). SEO requires that permits be obtained prior to drilling, and that wells be sited and constructed in accordance with published standards to protect the quality of the water and minimize potential for mechanical failure.

Potential impacts to groundwater from water use for the NPL Project could include the following:

1. The Wasatch Aquifer is the main source of groundwater in the region, and there is little recharge of the aquifer. As a result, removal of groundwater could result in a depletion of groundwater resources and impacts to stock wells and channel vegetation.
2. Groundwater removal could also potentially result in depression of the potentiometric surface or intrusion of lower quality water into fresh groundwater zones due to hydraulic changes.

These potential impacts are described in further detail below.

5.2.1 Depletion of Groundwater

Fresh groundwater is available primarily from the Wasatch Aquifer and to a lesser extent the Laney and Alluvial Aquifers. There are currently 31 stock water wells in the NPL Project Area that tap the permeable sandstone in the upper 1,100 feet of the Wasatch and shallow zones in the Alluvial and Laney Aquifers. One of the wells was drilled significantly deeper, 1,573 feet bgs, but is reported to produce from water-bearing zones above 860 feet (Wyoming SEO 2014). Five wells in the NPL Project Area are permitted to extract water for drilling, completion, dust suppression, and other oil and gas related activities at the JIDPA, and are completed in the upper 1,100 feet of the Wasatch Formation. Only two of these wells are currently operating. There are no industrial, agricultural, or domestic wells in the NPL Project Area. The stock wells use an estimated 19.2 acre-feet of water per year. The two Jonah water supply wells used approximately 47.0 acre feet of water in 2013. When combined, the water use in the NPL Project Area is estimated to be 66.2 acre-feet/year. Approximately one-third of the existing water use in NPL is not related to oil and gas activities and would be expected to continue regardless of oil and gas development. Summary statistics for existing JIDPA supply wells are provided in Table K-4, and well construction information and water quality data for these wells are summarized in Table K-5. Attachment B (*Water Supply Wells in and around the NPL Project Area*) provides a description of water supply wells, their location, permitted use, and other information for wells in and around the NPL Project Area. These data represent the best available existing information for water supply wells that could be used for the NPL Project. Implementation of the groundwater monitoring program prior to and during NPL Project development would provide additional information on groundwater conditions that inform development and monitoring.

Based on current use, depth, and water quality, the groundwater resources to be targeted for the NPL Project fall within the BLM definition of usable water, although the pH of the groundwater and the concentrations of TDS for some wells are outside the range of the EPA's Secondary Drinking Water Quality Criteria (EPA 2009). However, wells would not be used for potable water, and both pH and TDS within these concentration ranges can be effectively treated.

The amount of available water in the NPL Project Area is generally a function of the thickness and storage ability of the fresh water zones in the Wasatch. Well logs and well construction information demonstrate that the upper Wasatch, generally considered the upper 600 to 1,000 feet, contains the thickest and most permeable sandstone zones and is currently the only water source targeted in the Project Area (Phillips 2013b; Wyoming SEO 2014). Stock wells are variable in depth but generally produce from intervals shallower than the target zone for water for the project. Because of the nature of the water producing zones (isolated sands) the likelihood of well interference is low. Thinner permeable sands are present in the lower Wasatch, but it would be unnecessary to drill deeper into inferior aquifers with poor water quality when sufficient water of better quality is available at a shallower depth.

Based on an analysis of oil and gas well logs (Phillips 2013b) and completion information from existing water wells (Wyoming SEO 2014), the available water is contained in the upper 1,000 feet of the Wasatch and has over 500 feet of permeable sand aquifers for NPL Project water needs. This is consistent with the estimates used in the PAPA Hydrologic Model (Geomatrix 2008). Within the PAPA, the amount of available water in the Wasatch was roughly estimated using the lower end of the estimated storage coefficient for the Wasatch (S = 0.0001 (dimensionless)), the initial head of the aquifer (500 feet above the base of the aquifer), and the surface area of the project. When these parameters are applied to the NPL Project, the estimated aquifer storage is greater than 7,000 acre-feet. This estimate represents the low end estimate of the available water in the Wasatch, because there is likely fresh water below 1,000 feet and storage coefficient could be up to 0.001 (AMEC 2014). Based on the assumptions and estimates described above, current water use in the NPL Project Area represents approximately one percent of the available water storage.

Analyses of water level measurements from existing pumping wells have not been conducted in the JIDPA to evaluate the long-term trend of water levels in response to prolonged pumping or the recovery of aquifers after pumping. Most wells are not designed for access to measure water levels, or have pumps which restrict access (AECOM 2014), and observation wells are not available to monitor the long-term effects of prolonged pumping of the water supply wells and compare actual conditions to the predicted effects described in the JIDPA Groundwater Flow Model and Hydrologic Impact Assessment (HydroGeo 2004). Based on results from the JIDPA Model, drawdown of the potentiometric surface would occur up to four miles from the pumping wells and extend less than one mile outside the JIDPA boundary. Three stock wells within the JIDPA are within the predicted drawdown zone of greater than one meter (3.3 feet), and ten additional wells are within the 0.5 to 1 meter drawdown zone. Water levels naturally fluctuate by approximately 1.6 feet (0.5 meter), so recovery, or the no affect level, was determined to be 0.5 meters (HydroGeo 2004). Four wells outside the JIDPA and within the NPL Project Area are within the 0.5 to 1 meter drawdown zone. No stock or domestic wells outside the JIDPA or NPL Project Area would be affected by pumping. Recovery of the aquifer would likely occur within six years for rapid project development (250 wells per year for 12 years) (HydroGeo 2004). Groundwater would recover within half a year at a slower well construction rate (75 wells per year for 41 years). The JIDPA and PAPA hydrologic models, which are based on similar Wasatch Aquifer characteristics, both predict a limited area of drawdown influence and rapid recovery of wells following cessation of pumping. Additionally, the large spacing between the supply well locations and the lack of interconnectivity between the discrete sand lenses from which water is drawn suggests only localized and temporary impacts around the water supply well locations as a result of pumping for the NPL Project. Due to the extremely variable nature of the geologic conditions within the State of Wyoming, there are no SEO well spacing requirements in effect for the NPL Project Area; however SEO requires that wells be sited to protect from contaminant sources and interference between other wells and surface water resources. To reduce the likelihood of interference with stock wells or surface water/vegetation, water supply wells for drilling should maintain a safe setback distance based on the site-specifics characteristics of the water bearing zones.

In the JIDPA, the Corona 2-14 water supply well (Map Reference #61 on Figure K-8) was shut down due to contamination. Between 2009 and 2010, following cessation of pumping, the well showed significant recovery as indicated by a water level increase of over 12 feet (AECOM 2008; AECOM 2009; AECOM 2014; BP 2010; BP 2011; BP 2012; Linn Energy 2013). Since 2010, the well has shown more than three feet of recovery, indicating that recovery is ongoing. Data are not available to quantify the impacts from the continuation of pumping of JIDPA water supply wells at current levels to support NPL Project water use; however, no problems associated with water availability and well production have been reported in annual depletion reports to BLM. Additionally, withdrawal from the near-surface aquifers would remain relatively constant as NPL Project development and water use increases and JIDPA development and water use decreases. As a result, there would be no anticipated net change in groundwater levels or recovery compared to existing conditions.

Water level measurements have not been collected in the stock wells within the NPL Project Area during the operator's pre-development sampling and analysis program conducted by Trihydro. Most wells have pumps and have no access ports to conduct water level measurements. Additionally, the wells are designed for maximum water production, rather than for monitoring water level measurements. Stock wells produce water from different, unconnected, spatially limited sandstone lenses within the Wasatch Formation, and water level measurements would reflect a very localized condition. As a result, no analysis of the baseline conditions for water levels within the NPL Project can be made at this time; however, as indicated above there would be no anticipated net change in groundwater levels compared to existing conditions.

5.2.2 Hydraulic Effects from Groundwater Removal

The NPL Project Area is generally arid, receiving only 11 inches of precipitation annually, and with the high rates of evaporation, there is limited to no water available for recharge during most of the year. Recharge of the Wasatch Formation occurs close to the Wind River Range and Wyoming Range at the basin edges and to a limited extent within the Tea Kettle Butte area in the NPL Project Area (Figure K-14). Although the groundwater removed for the NPL Project would not be replaced, analysis of the time it would take to recover is evaluated below.

Attachment A (The *Groundwater Flow Model and Hydrogeologic Impact Assessment, Jonah Infill Drilling Project)* (HydroGeo 2004) summarizes results of a numerical model designed to simulate the regional effect on water resources from pumping groundwater from the Wasatch Aquifer. The model simulates withdrawal of groundwater from the upper 500 feet of the Wasatch Formation at the JIDPA and analyzes the effects of the withdrawals over a wide area that includes all of the NPL Project Area. Since the water supply wells for the JIDPA would also provide water for the NPL Project, the model provides the best available representation of the potential impacts of water withdrawal for the NPL Project. Results of this analysis are also discussed in the Final EIS for the Jonah Infill Drilling Project (BLM 2006b).

For the model, the pumping scenario was based on pumping from 25 water supply wells in the JIDPA over three scenarios as indicated below in Table K-9. These wells would also be pumped to supply water for development of the NPL Project. Pumping groundwater typically results in a localized lowering of the potentiometric surface (drawdown) during active pumping, and then after pumping is halted a recovery period occurs when water levels increase and eventually return to pre-pumping conditions. The amount of drawdown, the extent of the drawdown (known as the cone of depression), and the length of time for recovery are dependent on pumping rates and duration, and the hydraulic characteristics of the aquifer.

Three scenarios were modeled to simulate groundwater pumping to accommodate development of 3,100 natural gas wells in the JIDPA over varying time periods. The pumping rates and well installation rates in the model were adjusted to account for sufficient water for drilling the 3,100 JIDPA wells. The scenarios modeled and resulting years to recovery are presented in Table K-9. According to the report, seasonal variation of the potentiometric surface is typically 1.6 feet in the area. Thus, a drawdown of 1.6 feet was considered recovery for the model.

Table K-9. Results of Modeling Simulations of Water Supply Well Pumping for the JIDPA

Well Installation Rate (wells per year)	Duration of Drilling Operations (years)	Years to Recovery after Pumping Ends
75	41.3	0.5
150	20.7	4.0
250	12.4	6.0

Source: HydroGeo 2004.

The Jonah Infill Drilling Project Final EIS (BLM 2006b) indicates that the maximum drawdown under pumping conditions was estimated by the model to be approximately 10 feet. Under pumping conditions, the cone of depression extends approximately one mile beyond the JIDPA, where drawdown is between 3.3 and 1.6 feet, including to the south into the NPL Project Area. The area of depressed groundwater does not extend beyond the NPL Project Area.

Based on the depths of wells inventoried by USGS (USGS 2013) and the well information summarized in Attachment B (*Water Supply Wells in and around the NPL Project Area*), drawdown of 10 feet in this aquifer is not expected to impact current water users. Given the current light use of this groundwater resource within the groundwater drawdown area, recovery within six years would not likely affect current users. Also, a 10-foot drawdown in an aquifer that is thousands of feet thick is not expected to result in intrusion of lower quality groundwater to the fresh water zone. Groundwater elevations and water quality outside the NPL Project Area would not be affected by the withdrawal and use of water from the Wasatch Aquifer. The predicted model results could be verified by implementing a monitoring program as described in Section 6.2 (*Summary of Impacts*).

5.3 Water Quality Impacts from Injection of Formation Fluids

Formation fluids resulting from the NPL Project would be disposed in permitted Class II Underground Injection wells into the Fort Union Formation, similar to the injection wells used for the JIDPA. Construction of oil and gas wells would include cementing the intermediate casing from the Lance through the Fort Union which would protect groundwater zones in the Fort Union. Injection wells would be constructed in accordance with WOGCC requirements to isolate the injection zone and protect aquifers. To evaluate potential impacts of formation fluids injection, the quality of the groundwater resource in the injection zone and that of the formation fluids that would be injected are discussed below. The potential for vertical migration of formation fluids from the injection zone (generally deeper than 4,500 feet bgs) up to the shallower aquifers (less than 2,500 feet bgs) is also discussed.

5.3.1 Water Quality in the Injection Zone

As previously discussed in Section 4.2.2 (*Water Quality*), data from several JIDPA injection wells completed in the upper Fort Union (approximately 4,900 to 7,700 feet bgs) were obtained from WOGCC (2014) and are summarized in Table K-6. Water samples were collected after drilling the injection wells and prior to any injection of formation fluids. The data shows TDS concentrations from 30,000 to 55,000 mg/L. The chemical composition of the water is uniformly calcium chloride, with some wells exhibiting high sodium concentrations. The sulfate and bicarbonate levels are very low compared to chloride. The EPA Secondary Maximum Contaminant Level for drinking water is 500 mg/L for TDS and 250 mg/L for chloride (EPA 2009). Groundwater in the injection target zone has levels two orders of magnitude higher for both parameters, indicating that this is not a source of water supply for most applications.

WDEQ groundwater regulations (2015) would likely classify the Fort Union minimally as Class IV (B) industrial quality water because it has a TDS concentration in excess of 10,000 mg/L. Waters that meet quality criteria for higher use (i.e., domestic, agricultural, livestock, and fish/aquatic life) have lower TDS concentrations (from 500 to 5,000 mg/L) and require an aquifer exemption for injection into these aquifers. Because of the high TDS concentrations, the upper Fort Union would likely be considered a Class VI water source – unusable or unsuitable for use. WOGCC regulations for the injection of formation fluids under a Class II UIC permit only require an aquifer exemption if the water in the receiving zone is considered “fresh and potable water”, which is defined as water currently being used as a drinking water source or having a TDS concentration less than 10,000 mg/L. Injection into the Upper Fort Union is unlikely to require an aquifer exemption because the TDS is well above the 10,000 mg/L threshold. Onshore Order 2 defines “usable water” as generally those waters containing up to 10,000 ppm (10,000 mg/L) of TDS and provides requirements for reporting their presence and protecting degradation of these waters through proper isolation.

5.3.2 Characteristics of Formation Fluids

The characteristics of the formation fluids samples from the upper Lance Formation in the JIDPA are assumed to be representative of formation fluids that would be generated by the NPL Project and represents the best available existing information. In both fields, gas and water are produced from permeable sandstones at depths between 6,500 and 13,500 feet (Encana 2011b). Table K-10 presents results of water quality analyses for several producing wells in the upper Lance Formation. Formation fluids exhibit TDS in the range of 3,000 to 4,500 mg/L, which is an order of magnitude lower than groundwater in the Fort Union Aquifer into which it would be injected for disposal. The water is typically a sodium bicarbonate to sodium chloride composition. Given that groundwater in the Fort Union Formation has much higher concentrations of dissolved solids than the formation fluids, little to no impact on groundwater quality would be expected from injection of formation fluids into the Fort Union Formation.

Table K-10. Formation Fluids Analysis from Selected Lance Wells in the JIDPA

Well Name	Jonah COR 6-9	Jonah HF 5-20	Jonah HF 5-29	Jonah HF 6-17A	Jonah HAC 6-19	Jonah HF 11-30	Jonah HF 12-21
Sampling Date	05/28/11	05/26/11	05/26/11	05/26/11	05/26/11	05/26/11	05/26/11
Anions (mg/L)							
Chloride	594	796	1,194	830	613	934	832
Bicarbonate	1,754	1,439	1,708	1,481	1,630	1,286	1,298
Sulfate	16.4	5.40	2.69	27.1	3.12	18.8	7.26
Silica	62.0	56.7	72.5	65.9	66.5	63.1	71.5
Cations (mg/L)							
Sodium	1,062	1,068	1,402	1,121	1,028	1,099	1,040
Magnesium	1.60	1.52	2.64	1.55	1.34	1.98	1.86
Calcium	9.98	12.4	21.1	12.5	10.3	18.9	15.5
Strontium	0.69	0.75	1.12	0.80	0.67	1.06	0.81
Barium	2.25	1.87	2.44	1.54	1.70	4.58	1.66
Iron	7.89	1.45	3.00	1.97	2.53	2.84	5.70
Potassium	12.4	13.1	47.0	13.4	13.2	15.2	13.4
Manganese	0.05	0.09	0.04	0.05	0.08	0.11	0.08
TDS (mg/L)	3,522	3,396	4,456	3,557	3,370	3,446	3,287
pH	7.55	7.22	7.17	7.36	7.14	7.34	7.18

Source: Phillips 2013c.

mg/L milligrams per liter
TDS total dissolved solids

5.3.3 Potential for Migration from the Injection Zone to Shallow Groundwater Resources

Potential water quality impacts to shallow groundwater in the upper 1,000 feet of the Wasatch Formation could occur if there were a hydraulic connection and upward flow between the injection zone and the shallow aquifer, and the fluid migration resulted in concentrations that adversely affect water quality. There is a low probability that both of these mechanisms would be present in the NPL Project Area, as described below.

Upward migration requires a hydraulic connection between the injection zone and the better quality groundwater in shallower aquifers. This connection can be through natural geologic structural features, such as faults or fractures, or via improperly abandoned or poorly constructed or damaged wells.

The available data on structural geologic features within the NPL Project Area are limited, but the best available existing information indicates that there are few geologic structural features outside of the bounding faults on the JIDPA that border the NPL Project Area. One study (Siguaw and Friend 2004) interpreted a thrust fault just southwest of the JIDPA and seismic data indicated that the fault terminates in the lower Eocene strata (Fort Union Formation) and does not extend to the upper aquifer. The structural styles presented in the publically available literature for the Jonah and Pinedale areas show fault patterns that affect only strata below the lower Eocene strata and do not extend upward into the Wasatch Formation (Montgomery and Robinson 1997). Warner (2000) refers to the northern Jonah bounding fault as extending from surface to basement, but provides no data to support the interpretation. As described in Section 3.2, bounding faults at Jonah are non-transmissive and do not allow upward migration of fluids. A similar situation is expected to be present in the NPL Project Area because of the proximity and similarity in geologic conditions within the region. Based on these publicly available data, there is no indication that a naturally occurring transmissive fracture zone, such as a fault, is present in the NPL Project Area that is capable of transmitting formation fluids to the shallow aquifer. Because there is currently limited data to support this assertion, a groundwater monitoring program would be implemented to monitor water quality conditions prior to and during oil and gas development to evaluate the potential for fluid migration along existing faults and fractures.

Upward migration could also occur through improperly constructed or abandoned injection or production wells. Wells with inadequate cement seals or seals and casings that have been damaged or deteriorated, could allow migration from the reservoir zone upward into the shallow water aquifer. Construction of oil and gas wells would include cementing the intermediate casing from the Lance through the Fort Union which would protect groundwater zones in the Fort Union and ensure gas or fluids cannot migrate into usable groundwater. As shown on the cross-section in Figure K-4, many wells in the NPL Project Area and the JIDPA are constructed with surface casings and cement seals to a depth of 2,500 feet, which ensures the shallow aquifer is isolated from upward migration of high salinity deeper water. Further, if all procedures required by the UIC Class II permits are followed, it is unlikely that injection wells would be improperly abandoned, poorly constructed, or damaged to result in a vertical migration conduit. The cross section (Figure K-4) shows several wells with surface casing set at 1,000 feet. Water sources in the vicinity of existing wells with shallow casing could increase the potential for water quality impacts to shallow water zones. There is currently no evidence of impacts in areas of shallow surface casing.

5.4 Water Quality Impacts from Drilling and Completion

The following information pertaining to drilling practices in the JIDPA were obtained from Jonah Energy (Dubois 2014). In the JIDPA, wells are drilled in a manner to prevent contamination of groundwater. Surface casing is set to 2,500 feet, and cement is circulated to the surface to ensure a full and complete seal across the water zone. The well is drilled with freshwater mud to the total depth. The well bore is underbalanced or balanced in the Wasatch Formation to limit infiltration of drilling mud and mud filtrate into the water zones, and is overbalanced with depth in the Lance Formation (pay zone). The freshwater mud creates a “filter cake” coating and seals off sides of the well bore across the open lower Wasatch and Fort Union Formations. This seal helps prevent loss of circulation and avoids loss of fluids into higher porosity sands as mud weight is increased for penetration of the over pressurized Lance gas productive zones. Biodiesel is sometimes used in difficult drilling spots within the borehole to increase lubricity of the mud and overcome differential sticking of the drill pipe to the borehole wall. Finally, a 4 ½-inch production casing is run to the total depth and cemented up to approximately 4,000 feet below ground surface, leaving the section from 2,500 to 4,000 feet open (without cement). The cemented zone thickness has varied through the years. Because of the high salinity of groundwater in the Upper

Fort Union Formation, corrosion of steel casing has occurred in this zone. All natural gas wells now have cathodic protection components to prevent corrosion.

The NPL Proposed Action includes directional drilling to reduce surface disturbance and centralize facilities. Directionally drilled wells for the NPL Project may utilize oil-based muds in rare cases and based on site-specific considerations and water quality testing (i.e., total dissolved solids greater than 10,000 ppm). The use of oil-based mud is expected to be infrequent and site-specific, but could increase the possibility of introducing undesirable petroleum-hydrocarbon components into water bearing zones. A recent BLM study from the Fox Hills Aquifer in the Powder River Basin (BLM 2015a) quantified the volume of hydrocarbons lost during oil-based mud drilling, and evaluated the dispersion of the hydrocarbon material away from the borehole. The report concluded that use of oil based drilling mud will result in estimated conservative fluid loss of three to as much as 14 gallons (0.06 to 0.34 barrels) of hydrocarbons per well, with toluene and ethylbenzene being the largest components. Dispersion of maximum estimated hydrocarbon volumes over one acre of the Fox Hills Sandstone would result in concentrations below EPA drinking water standards. The geologic and drilling conditions represented in the Fox Hills study are similar to those expected in the Project Area and similar results would be expected. Additional precautions are taken, including the installation of an intermediate casing string set to below water-bearing sands to avoid infiltration into the formation. Since there is no definitive depth at which the Wasatch Formation changes from TDS less than 10,000 mg/L to TDS greater than 10,000 mg/L) the entire Wasatch Formation is considered usable water until otherwise demonstrated. Water-bearing sands in the upper Fort Union injection zone have been demonstrated to contain TDS concentrations well in excess of 10,000 mg/L (Table K-6).

Operator's in the JIDPA typically use freshwater from their industrial water supply wells for drilling fluids. They have used recycled formation fluids in the past; however, there were issues with bacterial growth, which reduced the ability of the mud to carry solids. The NPL Project operator has not yet determined the specific drilling plan for future wells, including those in the NPL Project Area, but vertical and directional wells will likely be drilled with freshwater mud, and drilling practices will likely be similar to those described above. After the well has been drilled, several operations are conducted to prepare the well for gas production. Collectively, the operations after drilling and before production are called completion activities. Completion activities include cleaning the drilling fluids from the hole through circulation of low solids fluids (such as freshwater or brine), placing and cementing casing into the borehole, perforating the casing to allow gas to flow into the well, hydraulically fracturing the perforated zone to enhance communication with the formation, cleaning the hydraulic fracturing material from the borehole, and setting hardware and production tubing in the well for production. These operations use various fluids with a wide range of properties and components to accomplish these tasks without affecting the producing formation. The operator has provided general information on well completion methods and materials for the NPL Project, which are described below.

Hydraulic fracturing is a well stimulation method used to increase the permeability of the gas-bearing sandstones to allow trapped gas to flow more easily to the wellbore for recovery. The process involves pumping a large volume of water and sand, along with small volumes of treatment chemicals, into the producing zone and increasing the pressure until the reservoir rock breaks down and creates fractures. Hydraulic fracturing programs are designed to maximize the area of interconnected fractures within the gas-bearing reservoir rock and not allow the fractures to propagate outside the gas-bearing zone. Pumping is continued for a short time until the fracture length is sufficient to increase gas permeability, and sand is pumped into the fractures to prop them open. After the fractures are propped open, the pressure is reduced, causing reversal of flow from the reservoir into the wellbore. This allows the excess fracturing fluids and sand to be removed from the wellbore and reservoir. This period is called the flowback period and can last from a few days to a few weeks. Brine or freshwater is circulated in the well to aid in the removal of hydraulic fracturing fluids and other fluids used during well completion.

While it is desirable to remove all the excess fluids and sand, only a portion of the initial fluids is recovered during the flowback period. The exact amount of flowback is determined by many factors including drilling methods, hydraulic fracturing design and execution, and reservoir rock characteristics. The total volume of recovered hydraulic fracturing fluids can range from 15 to 80 percent (Groat and Grimshaw 2012), with most of the recovery occurring early in the flowback period. It is expected that flowback recoveries will be near the upper end of this range for the NPL Project (Phillips 2013a). Some water and chemical components in the hydraulic fracturing and other completion fluids may adsorb to the minerals in the reservoir and may never be recovered. Naturally-occurring water in the formation that is produced along with the gas after the well is completed is called formation fluids. During the production period, some of the water introduced into the reservoir during well completion procedures is mobilized and mixed with the formation fluids. It is often very difficult to determine what part of the flowback fluids is from drilling and completion activities. The Low Level Petroleum Hydrocarbon study at PAPA (AMEC 2013b) tested flowback fluids in several wells at various times during the flowback period. The analysis concluded that the concentration of BTEX compounds increased with flowback time, indicating the presence of naturally occurring formation fluids.

Water quality impacts from well completion, including hydraulic fracturing, could include the following five scenarios (BLM 2013b):

1. Upward movement of hydraulic fracturing fluids and naturally occurring formation fluids through the rock layers above the producing zone in response to the elevated pressure required to hydraulically fracture the target gas-producing zone.
2. Contamination of aquifers through the introduction of drilling and/or completion fluids through spills or drilling problems such as lost circulation zones.
3. Communication of the induced hydraulic fractures with existing fractures potentially allowing fluid migration into water-bearing zones.
4. Cross-contamination of aquifers that may result when fluids from a deeper aquifer/formation migrate into a shallower aquifer/formation due to improperly cemented well casings.
5. Progressive contamination of deep confined, shallow confined, and unconfined aquifers if the deep confined aquifers are not completely isolated from shallower aquifers. An example of this would be salt water intrusion resulting from sustained drawdown associated with the pumping of groundwater.

Potential water quality impacts to the groundwater in the upper 1,000 feet of the Wasatch Formation described above could occur if there were a hydraulic connection and flow between the deeper impacted zone and the shallow aquifer and if the fluid migration results in concentrations that adversely affect water quality. These scenarios are described in further detail below.

Scenario 1 – Hydraulic fracturing induces a pressure pulse into the gas-producing formation in order to create fractures in the formation. Some authors (Myers 2012; Rozell and Reaven 2012; Warner et al. 2012) have theorized that this pressure pulse could force naturally-occurring fluids and hydraulic fracturing fluids upward through the rock column into the shallow useable water aquifers. Recently, Flewelling and Sharma (2014) demonstrated that the conditions required for rapid upward migration of hydraulic fracturing fluid or brine via bedrock would require both high rock permeability and high upward head gradients to be present in the rock column. Flewelling and Sharma (2014) demonstrate that these two conditions are mutually exclusive, and rapid upward migration of hydraulic fracturing fluid and brine through the entire rock column is not plausible based on the following conditions:

- Reservoir zones with upward gradients are generally overlain by low permeability rocks (reservoir seals) that would have long travel times for fluids moving through them. The pressure pulse generated by the hydraulic fracturing event is typically short, and the impacted rock layer is thin relative to the total thickness of the column between the hydraulically fractured zone and the upper water-bearing zone. The resulting pressure pulse would not be great enough to drive fluids through the low permeability rock above the hydraulically fractured zone and into the shallow water zone in a short period of time. Timescales for transport are long, often on the order of 10^6 years.
- After fracturing is completed and wells are producing fluids, the flow gradient is towards the borehole and is not directed upward, so the upward driving pressure is no longer dominant.

Measurements of vertical and horizontal hydraulic gradients between the Wasatch Formation and the deeper, poor water quality zones in the Fort Union and Lance Formations in the NPL Project Area are not documented because there are no observation wells completed in these zones. In general, where these rocks (i.e., formations) are exposed at the edge of the GRB, the gradient is downward and towards the center of the basin because of the recharge areas (Bartos and Hallberg 2010). However, locally there may be upward vertical gradients (Bartos and Hallberg 2010). While there may be local upward gradients, the lack of hydraulic connections between the zones and the distance between them suggest there is a low likelihood of upward migration of completions fluids and naturally occurring formation fluids.

Scenario 2 – Contamination of aquifers could occur if drilling or completion fluids, or other hazardous or non-hazardous materials are accidentally spilled at the surface and percolate downward into the upper aquifer. Refer to Section 4.7 (*Hazardous and Non-Hazardous Materials*) in the NPL Project EIS for more information on the potential for accidental spills and leakages of hazardous and non-hazardous materials. Lost circulation can occur during drilling when mud and cuttings are not returned to the surface from downhole well location. These conditions exist when high permeable zones, such as fractures, conduits, and unconsolidated sands, are encountered and mud exits the borehole into the formation instead of continuing up the borehole to the surface. The drilling mud, including any additives and lost circulation control materials, can invade the permeable zone and could affect the water quality of the water bearing zones.

These potential impacts are minimized when the surface casing is set at the proper depth to isolate the water-bearing zones, and the cement quality ensures the complete isolation of the zones from upward flow in the well. For the NPL Project Proposed Action, surface casing would be set to a depth of 2,500 feet. Currently the deepest drilling water supply well is 1,573 feet. Refer to Attachment B (*Water Supply Wells in and around the NPL Project* Area) for a list of water supply wells, their depths, and other information. Well completion and casing procedures required by BLM, WOGCC, and other regulatory authorities are designed to ensure the surface casing protects aquifers. BLM requirements for completion and casing procedures are found in 43 CFR 3160 and Oil and Gas Onshore Order No. 2. The WOGCC requirements are located in Chapter 3 Section 22 of the operational and drilling rules (WOGCC 2008). The Resource Protection Measures in Appendix B of the NPL Project EIS and other best management practices during drilling and completions, including maintaining proper mud weight and properties, monitoring mud flow returns and drilling rates, and anticipation of known zones of high permeability, would reduce the potential impacts to groundwater resources associated with lost circulation zones.

Scenario 3 – The potential for impacts from communication with existing fractures is dependent on the presence, orientation, and density of natural fractures and the local hydraulic gradients that drive fluid flow. To date, the connection of hydraulic fractured zones with natural fractures that mobilize fluids to shallow water is an unproven theory (BLM 2013a). Recent studies by EPA indicate that the possibility of fault reactivation creating a pathway to shallow groundwater is remote (EPA 2012). The risk of induced fractures extending out of the target formation into an aquifer depends, in part, on the formation thickness separating the targeted fractured formation and the aquifer, as well as the physical properties, types, thicknesses, and depths of the targeted formation and surrounding geologic formations. Operators generally design hydraulic fracturing programs to contain the fractures within the target formation because fractures that extend outside the target zone do not benefit production and could intersect water-bearing strata or unproductive zones, thus incurring additional cost without increasing production. There is a limit to how much a fracture can grow vertically, even in the most advantageous conditions. Fisher (2010) plotted fracture depths (determined by microseismic monitoring) versus aquifer depths (from USGS) for thousands of wells in the Barnett, Woodford, and Marcellus Shales, similar in depth to the Lance Pool (the target zone for NPL Project drilling, completions, and production), to demonstrate the vertical separation between induced fractures and aquifers. Warpinski (2011) reviewed this data and determined that the microseismic data set includes induced fractures that intersect naturally occurring fractures. Warpinski (2011) concluded that while fractures do occasionally intersect faults and other fracture systems, the data shows that vertical growth is limited when this occurs because the stress regime favors more horizontal fracturing closer to the surface. Warpinski (2011) also noted that some of the largest fractures occur where a fault has been intersected, but growth is equally likely to be downward and upward.

In the NPL Project Area there is a relatively large distance between the producing zone in the Lance Formation and the shallower, Wasatch Formation. As described above in Section 3.3 (*Geology and Stratigraphy),* these zones are separated by low-permeability strata. As shown on the cross-section in Figure K-4, the distance is greater than 5,000 feet between the producing zone (Lance Formation) and the overlying currently used water (upper 1,000 feet of the Wasatch) and could exceed 9,000 feet. Well logs show the intervening layers include thick zones of shale and silt with extremely low permeability. Warner (2000) describes the shales in the Fort Union as a reservoir seal for the Lance Formation gas, indicating that the Fort Union is an effective and impermeable barrier to upward migration. Based on the thickness and geologic characteristics of the formations, there is a low likelihood of hydraulic fractures communicating with natural fractures between the producing and source water zones in the NPL Project Area.

Scenario 4 – Construction, drilling, maintenance, and operation of water source wells, gas production wells, and injection wells would be conducted in accordance with all permit requirements and in compliance with other plans, policies, regulations, procedures and resource protection measures in Appendix B (*Resource Protection Measures*) of the NPL Project EIS. Application of proper construction, drilling, operation, and maintenance activities in accordance with plans, policies, and regulations would limit the potential for contamination of aquifers, as discussed in Scenario 2. Additionally, as discussed above, the geologic characteristics of the Lance and Fort Union Formations provide an effective and impermeable barrier to upward migration of potential contamination (if it were to occur) from the Lance Formation to the shallower, Wasatch Formation.

Scenario 5 – Sustained pumping of groundwater may result in encroachment of lower quality water if the pumping creates a flow gradient of high TDS water toward the well intake point. This process, referred to as salt water intrusion, has been observed in coastal aquifers where seawater is adjacent to the freshwater lens and the wells area of influence extends outward into the seawater zone. Vertical intrusion can occur when water with higher TDS is pulled upward into the well (upconing) through aggressive or sustained pumping, where a relatively thin freshwater zone sits directly above a lower quality water zone. In both cases a hydraulic connection between the intake point of the well and the higher TDS water zone is necessary. Water supply wells at JIDPA are screened in the upper 600 to 1000 feet of the Wasatch Formation, and water with higher TDS is found in the lower portion of the Wasatch at depths greater than 2,500 feet. The freshwater and high TDS water are separated by over 1,500 feet of low permeability rocks; therefore, it is very unlikely that pumping in the isolated sands within the upper Wasatch Formation would induce upward flow from the lower Wasatch Formation through 1,500 feet of low permeability rocks.

Additionally, as discussed above, potential contamination would be minimized through proper construction, drilling, and operational procedures in accordance with applicable permits and regulations and because the surface casing would be set at a proper depth to isolate the fresh water zones, and the cement quality would ensure~~s~~ the complete isolation of water-bearing zones from upward flow in the well. Additionally, as discussed above, the geologic characteristics of the Lance Formation and Fort Union Formation provide an effective and impermeable barrier to upward migration of potential contamination in the production zone and injection zone (if it were to occur) to the shallower, Wasatch Formation. As a result, the potential for progressive contamination of deep confined, shallow confined, and unconfined aquifers, including the upper Wasatch Formation, is minimal.

Drilling and hydraulic fracturing activities have the potential to result in well bore collisions and frac hits if drilling of wells occur in close proximity to existing or additional new wells. Collisions and frac hits can result in loss of well control and potential release of drilling, completion and formation fluids to shallow aquifers and the surface. Well bore collisions occur when the drill bit deviates from the planned trajectory and accidentally intersects an existing wellbore. Directionally drilled well paths are planned prior to drilling and are designed to avoid adjacent wellbores by maintaining a minimum separation distance between wells. The distance between wells is maintained by monitoring the trajectory of the wellbore during drilling using directional sensors mounted near the drill bit, or by running a wireline directional survey tool. Frac hits, also called inter wellbore communication, occur when the pressure pulse from a well undergoing hydraulic fracture stimulation is transmitted to an adjacent well, either through interconnected fractures or improperly sealed casing. If the wells are weakly connected the effect of the pressure pulse is relatively small and may only register as a slight instantaneous increase in well pressure or a decrease in well production. For wells in close communication the sudden unexpected increase of pressure in the adjacent well can force fluids into the well at high pressure and result in loss of well control and release of completion and formation fluids to shallow aquifers and the surface. The EPA (2015) identified 10 incidents in the U.S. in which fluid spills were attributed to frac hits.

Wellbore collisions have potential to occur in the deviated part of the well when the measured trajectory of an existing well, or the new well is not accurately determined, or when the safety factor for the minimum separation distance between the wells is small. Wellbore collisions are most likely to occur at shallow depths, where the greatest well density exists (DeWardt et al. 2013). Successful collision avoidance management includes having an accurate description of the existing nearby well locations and trajectories, designing and maintaining a safe wellbore separation, and communicating the risks and avoidance procedures between those involved in the planning and drilling process (ISCWSA 2014). Hydraulic fracturing of wells drilled in close proximity to existing wells has a higher likelihood of affecting nearby wells, as do wells drilled from the same pad, and older wells with poor quality cement and casing (EPA 2015). A study of frac hits in the Woodford shale in Oklahoma showed that the likelihood of a communication event was less than 10 percent in wells more than 4,000 ft. apart, but rose to nearly 50 percent in wells less than 1,000 ft. apart (Montague and Pinder 2015). The results of this study are included to disclose the most recent literature on communication events. The outcome of this study may not be transferrable to the NPL Project or Project Area due to differences in hydrogeologic conditions, project-specific activities and procedures, and other factors.

A draft Industry Recommended Practice for the Canadian Oil and Gas Industry has been developed for minimizing Interwellbore Communication (Enform 2015) and states that the likelihood and potential impacts of frac hits can be reduced by designing and monitoring fracture treatments to control the length of fractures, and working with nearby well owners to temporarily shut in producing wells that may be potentially at risk during well stimulation activities. There are no known occurrences of fluid releases from frac hits in Wyoming or within the analysis area. Requirements for directional well planning and directional well surveys are provided in WOGCC Rules Chapter 3 Section 25. If all wells are designed and drilled in accordance with applicable WOGCC regulations it is assumed that these impacts would not occur. Additional analysis of potential for wellbore collisions and frac hits would occur during site-specific permitting at the APD level once specific drilling and well locations are known in relation to other existing and proposed new wells.

6.0 SUMMARY AND CONCLUSIONS

6.1 Conceptual Site Model for the NPL Project Area

This section summarizes current understanding of the hydrologic systems within and around the NPL Project Area. It is based on a synthesis of existing lithologic, hydrologic, climatological, and water quality data for both surface water and groundwater resources presented in the sections above. The NPL Project Area is in a semi-arid region with low precipitation and high evaporation rates that result in little to no recharge through surficial soils to groundwater. The NPL Project Area is drained by ephemeral streams that flow in response to spring snowmelt from the mountains to the north and east. A drainage divide runs through the NPL Project Area, with the western portion draining to the Green River, and the eastern portion draining to the Big Sandy River.

Fifteen HUC-12 level watersheds intersect the NPL Project Area. In general, watersheds overlapping the western portion of the NPL Project Area drain to tributaries of the Green River, while those overlapping the eastern portion of the Project Area drain toward the Big Sandy River, which ultimately discharges to the Green River, approximately 28 miles south of the NPL Project Area. No surface water quality data from within the NPL Project Area were identified; however, general surface water quality can be inferred from the receiving perennial waters of the drainage area, which are the Green River and the Big Sandy River. The quality of runoff is largely dependent upon the amount of salts, sediments, and organic materials that accumulate in dry stream channels during periods of runoff. TDS resulting from agricultural runoff and energy development are elevated and are a water quality concern in the Green River and Big Sandy River drainage areas.

The BLM used the AGWA model (BLM 2013a) to identify areas that are susceptible to changes in land cover, surface-disturbing activities, and/or climate. The present (existing conditions) show that more than 86 percent of the existing stream miles exhibit low to very low impacts. Areas of moderate to high impact account for approximately five percent of the analysis area and occur in portions of the Lower Alkali Creek, Chapel Canyon, Spring Creek – Green River, Reardon Draw, Jonah Gulch, Long Draw, and Little Colorado Watersheds. Much of the moderate and high impact area is outside the NPL Project Area, in the lower reaches of drainages near the Big Sandy and Green Rivers.

Recharge of groundwater from surface infiltration occurs mainly at the edges of the basin outside of the NPL Project Area, along the base of the mountains. A small area of permeable surface material exists in the NPL Project Area near Tea Kettle Butte (Figure K-14) and allows for some infiltration, but because of the low precipitation and high evaporation, recharge is generally insignificant. There is likely some groundwater exchange between the Laney and adjacent Wasatch beds, due to the lack of hydraulic barriers between the two zones and the gentle dip of the rocks to the southwest. Based on the best available existing information, the Wasatch Aquifer is not thought to discharge to surface water, although a complete analysis of vertical hydraulic gradients has not been completed.

Four important water-bearing zones are identified for the NPL Project Area, including the following:

- **Alluvial Aquifer –** Discontinuous alluvial deposits form isolated aquifers in a few areas of the NPL Project Area, but they are also not considered an important groundwater resource. Where the Alluvial aquifer is present, it is likely hydraulically connected to surface waters and would drain to and recharge the surface water. The Alluvial aquifer does not provide water for any of the wells in the NPL Project Area, but the springs may represent groundwater breakouts of water from the Alluvial aquifer.

- **Laney Aquifer –** This unit is thin (less than 200 feet thick) and made up of limestone, sandstone, marlstone, and thin shales. The Laney aquifer is found at ground surface in the central, southern, and eastern portions of the NPL Project Area. Four stock wells produce water from this zone in the NPL Project Area (Attachment B). The Laney aquifer is not identified as an important water resource or a target zone for NPL Project operations due to poor permeability and low yield.
- **Wasatch Aquifer–** The Wasatch Aquifer is the primary aquifer in the NPL Project Area and adjacent areas. The uppermost 600 to 1,000 feet of the Wasatch contains numerous thick sandstone layers that provide the source of water in stock wells and for oil and gas drilling operations at JIDPA and PAPA. West of the NPL Project Area, the Wasatch Aquifer may discharge to the Green River.
- **Fort Union Aquifer–** Permeable sandstone layers within the Fort Union Formation are classified by Bartos and Hallberg (2010) as the Fort Union Zone of the Wasatch-Fort Union Aquifer system (referred to here as the Fort Union Aquifer). The water quality is generally poor due to high TDS, and the aquifer is not used for domestic, agricultural, or livestock water uses in the analysis area. The Fort Union Aquifer is the target zone in the JIDPA for injection of formation fluids.

There have been few studies of the structural geology of the NPL Project Area. Compared to the JIDPA and PAPA to the north, which have been studied, the NPL Project Area has a less complex geologic history and fewer structural features, including faults and fractures. Minimal natural vertical conduits are expected that would provide hydraulic conductivity between the targeted formation fluids injection zone and the gas producing zone.

Water for the NPL Project would be removed from the top 1,000 feet of the Wasatch Formation from wells in the JIDPA and the NPL Project Area. Geochemical data indicate that the groundwater removed to date in the JIDPA contains elevated levels of TDS and pH greater than EPA (2009) Secondary MCLs for drinking water but is usable for livestock watering purposes and, if treated, other domestic uses. Groundwater quality in the Fort Union Aquifer is of low quality due to naturally occurring high TDS content.

6.2 Summary of Impacts

This section summarizes the potential impacts to surface water and groundwater resources resulting from the NPL Project. Additional information on these potential impacts can be found in the sections above. Refer to Chapter 4 (*Environmental Consequences*) of the NPL Project EIS for a comparative analysis of potential impacts to surface water and groundwater resources resulting from the NPL Project Proposed Action and alternatives.

The primary effect of oil and gas development on the surface water systems within the analysis area would be related to increased sedimentation and channel erosion. Results of the AGWA model (BLM 2013a) indicate there is a low probability of transporting sediment and salt from contributing watersheds to major stream channels for all of the modeled development scenarios. However, heavy storms may increase the probability of impacts to tributaries of the Green and Big Sandy Rivers, as well as the rivers themselves, especially in watersheds where development may be concentrated and sediment transport is more likely.

Groundwater to be used for the NPL Project would be permanently removed from the upper 1,000 feet of the Wasatch Formation for well drilling and cementing. Approximately 29 percent of the water used for the NPL Project Area would come from existing and potential new wells targeting the Wasatch and Fort Union Aquifers. Groundwater modeling results for the JIDPA and surrounding analysis area (including the NPL Project Area) described in Appendix A *(Groundwater Flow Model and Hydrogeologic Impact Assessment, Jonah Infill Drilling Project)* show that withdrawal of groundwater during active pumping would result in a localized lowering of the potentiometric surface within a few miles of the JIDPA of up to 10 feet. The lowered potentiometric surface would be greatest within a few miles of the JIDPA (proximate to the location of water supply wells) and would be expected to recover in less than six years. The area of depressed groundwater would not extend outside of the NPL Project Area. Groundwater elevations and water quality outside the NPL Project Area would not be affected by the withdrawal and use of water.

Drawdown associated with the JIDPA and transitioning to the NPL Project would not intersect or induce upward flow from the Fort Union Aquifer, located more than 3,500 feet below the water supply well intake zones. Adherence to BLM and WOGCC well construction and operation requirements would ensure the wells are not conduits for upward migration of fluids into the zones. Existing effects of water drawdown observed at the JIDPA would likely continue but not change in magnitude, because the total water withdrawal from the near-surface aquifers would remain reasonably constant as NPL Project drilling increases and JIDPA drilling decreases. Prolonged drought conditions could exacerbate the lowering of the potentiometric surface and lengthen the time for recovery.

Oil-based mud, which may be used to drill wells depending on site-specific conditions (i.e., total dissolved solids greater than 10,000 ppm), and biodiesel, an additive used to address problems and difficult drilling conditions, have the potential for loss into water-bearing zones during drilling. The risk of impact from loss of these fluids is minimal due to the small volume of hydrocarbons that would be lost to the formation and the limited distance of infiltration of the hydrocarbons. Impacts would be minimized through the use of proactive drilling mud management programs, which create and maintain an impermeable filter cake on the borehole wall, and casing and cement programs that ensure isolation of the water-bearing zones.

More than 71 percent of the total amount of water used for the NPL project would support well completion, and would come from recycled sources from the Jonah formation fluids treatment facility. The use of recycled water reduces the need for freshwater withdrawal and would reduce the potential impacts related to water withdrawal.

Formation fluids would be injected into the Fort Union Aquifer. Since formation fluids would have TDS levels significantly lower than the levels of the groundwater in this aquifer, no adverse impacts to groundwater quality in the Fort Union Aquifer are expected. Vertical migration of formation fluids into the shallow Wasatch Formation is unlikely through natural conduits, because there is insufficient head pressure to drive the dense brine through the 3,500-foot separation, which contains multiple low permeable layers. Additionally, adherence to BLM and WOGCC well construction and operation requirements would ensure the injection wells are not conduits for upward migration of fluids into shallow water-bearing zones.

The NPL Project target zone for gas production, that would include completion operations in the Lance Formation, is approximately 5,000 to 9,000 feet below the deepest currently used groundwater source, and 3,500 to 7,500 feet below the lowest potential source of low TDS water (the base of the Wasatch Formation). No existing hydrologic mechanisms or conditions have been identified that would allow completion fluids to be driven through the intervening rocks as a result of normal completion operations. Well construction and operation practices required by BLM and WOGCC ensure would ensure that the wellbores do not provide a pathway for transport of fluids from the producing zone to the shallow water-bearing zones.

Implementation of an NPL Project groundwater monitoring program prior to and during development would provide additional information on hydrogeological conditions, water quality, water levels and other information to inform proper drilling and operational activities and would provide a mechanism for early identification and remedy of impacts, if they were to occur. This effort would consist of a groundwater baseline study, groundwater and surface water monitoring, and installation of additional monitoring wells, as needed. The program would include routine sampling of existing water sources and new monitoring wells as NPL development progresses with implementation of appropriate safeguards and BMPs during all phases of development. Data would be used to validate the results of the predictive groundwater model.

7.0 REFERENCES

AECOM. 2008. Submittal of Results – BLM/WDEQ Monitoring Request; Water Supply Wells, Jonah Field 2008. Letter Report submitted to BP Jonah Operation Center. December 22.

AECOM. 2009. Submittal of Results for the BLM/WDEQ Monitoring Request; Water Supply Wells, Jonah Field 2009. Letter Report submitted to BP Jonah Operation Center. September 30.

AECOM. 2011. Submittal of Results for the BLM/WDEQ Monitoring Request for the Water supply Wells at Jonah Field, 2010. Letter Report submitted to BP Jonah Operation Center. January 17.

AECOM. 2014. Submittal of Results for the BLM/WDEQ Monitoring Request for the Water Supply Wells at Jonah Field, 2013. Letter Report submitted to Linn Energy. January 16.

AMEC Environment and Infrastructure, Inc. (AMEC). 2010. Encana Annual Groundwater Monitoring Results – 2009, Jonah Field, Sublette County, Wyoming. Letter Report submitted to Encana. January 27.

AMEC Environment and Infrastructure, Inc. (AMEC). 2012. Hydrogeologic Data Gaps Investigation Interim Plan. Pinedale Anticline Project Area ROD, Sublette County, Wyoming. Final Technical Report. May.

AMEC Environment and Infrastructure, Inc. (AMEC). 2013a. Numerical Groundwater Modeling report, Pinedale Anticline Oil and Gas Exploration and Development Project, Sublette County, Wyoming. Final Report. October.

AMEC Environment and Infrastructure, Inc. (AMEC). 2013b. Final Technical Report, Evaluation of Potential Sources of Low-Level Petroleum Hydrocarbon Compounds Detected in Groundwater, Interim Plan, Pinedale Anticline Project Area ROD, Sublette County, Wyoming. Prepared for the U.S. Department of the Interior, Bureau of Land Management, Pinedale Field Office. October.

AMEC Environment and Infrastructure, Inc. (AMEC). 2013c. Encana Annual Groundwater Monitoring Results – 2012, Jonah Field, Sublette County, Wyoming. Letter Report submitted to Encana. January 25.

AMEC. 2014. Encana Annual Groundwater Monitoring Results – 2013 Jonah Field, Sublette County, Wyoming. Letter Report submitted to Encana. January 10.

Bartos, T., and L. Hallberg. 2010. Chapter 5: Groundwater and Hydrogeologic Units in Green River Basin Water Plan II – Groundwater Study Level I (2007–2009). Prepared for the Wyoming Water Development Commission. Laramie, Wyo. August. Accessed September 12, 2013. Available online: http://waterplan.state.wy.us/plan/green/2010/gw-finalrept/gw-finalrept.html.

Bartos, T., L. Hallberg and M.L. Clark. 2010. Chapter 6: Groundwater Quality in Green River Basin Water Plan II – Groundwater Study Level I (2007–2009). Prepared for the Wyoming Water Development Commission. Laramie, Wyo. August. Accessed September 12, 2013. Available online: http://waterplan.state.wy.us/plan/green/2010/gw-finalrept/gw-finalrept.html.

Bedessem, M.E., B. Casey, K. Frederick, and N. Nibbelink. 2005. Aquifer Prioritization for Ambient Ground Water Monitoring. Groundwater Monitoring & Remediation, 25: 150-158.

BP America Production Company (BP). 2004a. Jonah Field – Sublette County, Wyoming, Fresh Water Supply Wells. Letter Report submitted to the Bureau of Land Management. August 10.

BP America Production Company (BP). 2004b. Jonah Operations Center: Jonah Area Operations, Fresh Water supply Wells – Jonah Field. Letter Report submitted to the Bureau of Land Management. November 2.

BP America Production Company (BP). 2009. Jonah ROD Requirements. Letter Report submitted to the Bureau of Land Management, Pinedale Field Office. January 27.

BP America Production Company (BP). 2010. Jonah ROD Requirements. Letter Report submitted to Wyoming Department of Environmental Quality, Water Quality Division. January 8.

BP America Production Company (BP). 2011. Jonah ROD Requirements. Letter Report submitted to Wyoming Department of Environmental Quality, Water Quality Division. January 21.

BP America Production Company (BP). 2012. Jonah ROD Requirements. Letter Report submitted to Wyoming Department of Environmental Quality, Water Quality Division. January 15.

Bureau of Land Management (BLM). 2006a. Clarifications on the Jonah Infill Drilling Project (JIDPA) Record of Decision Requirements. Letter from the Bureau of Land Management to BP. October 2.

Bureau of Land Management (BLM). 2006b. Final Environmental Impact Statement, Jonah Infill Drilling Project, Sublette County, Wyoming (BLM Document No. BLM/WY/PL-06/006+1310). Available online: http://www.blm.gov/wy/st/en/info/NEPA/documents/pfo/jonah.html.

Bureau of Land Management (BLM). 2006c. Record of Decision Jonah Infill Drilling Project, Sublette County, Wyoming (BLM Document No. BLM/WY/PL-06/006+1310). Available online: http://www.blm.gov/wy/st/en/info/NEPA/documents/pfo/jonah.html.

Bureau of Land Management (BLM). 2008. Pinedale Field Office Approved Resource Management Plan and Record of Decision.

Bureau of Land Management (BLM). 2013a. Modeling the Effects of Surface Disturbance using the Automated Geospatial Watershed Assessment (AGWA) Tool – Technical Report. August. Included as an appendix to the NPL Project EIS.

Bureau of Land Management (BLM). 2013b. Hydraulic Fracturing White Paper. Wyoming State Office. August 2013.

Bureau of Land Management (BLM). 2015a. Impacts of Oil Based Mud Use While Drilling the Fox Hills Sandstone in Northern Converse County Wyoming. Wyoming State Office. January 2015.

Bureau of Land Management (BLM). 2015b. List of wells drilled in JIDPA between 2008 and 2014. Pinedale Field Office, Wyoming. March 2015.

Camp, W.K. 2008. Basin-centered gas or subtle conventional traps? In S.P. Cumella, K.W. Shanley, and W.K. Camp, eds. Understanding, exploring, and developing tight-gas sands: 2005 Vail Hedberg Conference: AAPG Hedberg Series 3, p. 49–61.

Chafin, D.T., and Kimball, B.A., 1992. Ground-Water Geochemistry of the Near-Surface Wasatch Formation, Northern Green River Basin, Sublette County, Wyoming. U.S. Geological Survey Water-Resources Investigations Report 91-4069.

Clarey, Keith, and David Copeland. 2010. Chapter 4: Groundwater recharge, discharge and storage in Green River Basin Water Plan II – Groundwater Study Level I (2007–2009). Prepared for the Wyoming Water Development Commission. Laramie, Wyo. August. Accessed September 12, 2013. Available online: http://waterplan.state.wy.us/plan/green/2010/gw-finalrept/gw-ch04.html.

Clarey, Keith, and M.L. Thompson. 2010. Chapter 2: Study area in Green River Basin Water Plan II – Groundwater Study Level I (2007–2009). Prepared for the Wyoming Water Development Commission. Laramie, Wyo. August. Accessed September 12, 2013. Available online: http://waterplan.state.wy.us/plan/green/2010/gw-finalrept/gw-ch02.html.

Clarey, Keith. 2010. Chapter 3: Groundwater resources in Green River Basin Water Plan II – Groundwater Study Level I (2007–2009). Prepared for the Wyoming Water Development Commission. Laramie, Wyo. August. Accessed September 12, 2013. Available online: http://waterplan.state.wy.us/plan/green/2010/gw-finalrept/gw-ch03.html.

DeWardt, J., S. Mullin, J. Thorogood, J. Wright, R. Bacon. 2013. TechBits: Well Bore Collision Avoidance and Interceptions - State of the Art. Journal of Petroleum Technology. Vol. 65, Issue 3. Pages 42-50.

Drucker, Sam. 2016. Personal communication from Sam Drucker (Pinedale Field Office, Bureau of Land Management) regarding surface water expressions/seeps in the Teakettle Dune Field within the NPL Project Area. Input provided as part of BLM ID Team review and comment on the NPL PDEIS, provided January 8, 2016.

DuBois, Dean. 2014. Drilling Practices in the Jonah/NPL. Phone Conversation with Dean DuBois (Encana/Jonah Energy) and Janet Bellis (BLM). May 8.

Dubois, DP. 2013. NPL Project S-N xsec all zones. Email from Randy Phillips (Encana) to Alan Rabinoff (ICF) containing cross-section drawing. August 20.

Eltschlager, K.K., J.W. Hawkins, W.C. Ehler, and F. Baldassare. 2001. Technical Measures for the Investigation and Mitigation of Fugitive Methane Hazards in Areas of Coal Mining. Department of the Interior, Office of Surface Mining Reclamation and Enforcement. Pittsburg, Pennsylvania. September.

Encana Oil and Gas, USA (Encana). 2009. 2008 Yearly Sampling Report of Industrial Water Wells, Jonah Infill Drilling Project, Sublette County, WY. Letter Report submitted to the Bureau of Land Management. June 30.

Encana Oil and Gas, USA (Encana). 2010. Operations Reports and Emissions Reduction Report, Jonah Infill Drilling Project, Sublette County, WY. Letter Report submitted to Jonah Interagency Mitigation and Reclamation Office and the Bureau of Land Management. January 28.

Encana Oil and Gas, USA (Encana). 2011a. Application for Underground Disposal of Water, Hacienda 4-1, Jonah Field, API 4903523237

Encana Oil and Gas, USA (Encana). 2011b. Plan of Development for Normally Pressured Lance Gas Development Project, Sublette County, Wyoming. June 11.

Encana Oil and Gas, USA (Encana). 2014. Operations Reports and Emissions Reduction Report, Jonah Infill Drilling Project, Sublette County, WY. Letter Report submitted to Jonah Interagency Mitigation and Reclamation Office and the Bureau of Land Management. January 31.

Enform. 2015. Drilling and Completion Committee Draft IRP 24: Fracture Stimulation An Industry Recommended Practice (IRP) for the Canadian Oil and Gas Industry, For Industry Review Rev 03, May 2015. 85 pp. Available online: http://www.enform.ca/resources/detail/29/dacc-irp-volume-24-fracture-stimulation.

Environmental Protection Agency (EPA). 2009. National Drinking Water Regulations. EPA 816-F-09-0004, May. Available online: http://water.epa.gov/drink/contaminants/index.cfm#List.

Environmental Protection Agency (EPA). 2012. Study of the Impacts of Hydraulic Fracturing on Drinking Water Resources: Progress Report December 2012. Available online: http://www2.epa.gov/hfstudy/potential-impacts-hydraulic-fracturing-drinking-water-resources-progress-report-december.

Environmental Protection Agency (EPA). 2015. Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resource; External Review Draft, EPA/600/R-15/047a. June 2015. (Accessed at http://www.epa.gov/hfstudy).

Fisher, M.K. 2010. Data Confirm Safety of Well Fracturing. American Oil and Gas Reporter. July.

Flewelling and Sharma. 2014. Constraints on Upward Migration of Hydraulic Fracturing Fluid and Brine. *Ground Water*, 52:1, 9-19.

Geomatrix Consultants, Inc. (Geomatrix) 2008. Final Hydrogeologic Conceptual Model, Pinedale Anticline Project Area, Sublette County. Consultants report prepared for the following: Shell Rocky Mountain Production, Ultra Petroleum Corporation, Questar Market Resources, BP America Production Company, Yates Petroleum Company, 51 p.

Glover, K.C., Naftz, D.L., and Martin, L.J., 1998. Geohydrology of Tertiary Rocks in the Upper Colorado River Basin in Colorado, Utah, and Wyoming, Excluding the San Juan Basin. U.S. Geological Survey Water Resources Investigation Report 96-4105.

Grid Petroleum Corp. 2010. SE Jonah Initial Technical Review. May. Accessed September 9, 2013. Available online: http://www.gridpetroleum.com/wp-content/uploads/2011/02/SE-Jonah-Initial-Technical-View.pdf.

Groat, C.G., and T. Grimshaw. 2012. Fact-Based Regulation for Environmental Protection in Shale Gas Development. A report by The Energy Institute, University of Texas, Austin. February 15.

Hamerlinck, J.D., and C.S. Arneson (eds). 1998. Wyoming ground water vulnerability assessment handbook: Volume 1. Background, model development, and aquifer sensitivity analysis. Spatial Data and Visualization Center Publication SDVC Report 98-01. University of Wyoming, Laramie, WY.

Harris, Nicholas; Philp, Paul; Lewan, Michael. 2013. Application of Natural Gas Composition To Modeling Communication Within And Filling Of Large Tight-Gas-Sand Reservoirs, Rocky Mountains. December 20, 2013. Available online at: https://www.netl.doe.gov/file%20library/Research/Oil-Gas/Natural%20Gas/shale%20gas/07122-09-final-report.pdf

HydroGeo, Inc. 2004. Groundwater Flow Model and Hydrologic Impact Assessment, Jonah Infill Project EIS. Prepared for TRC Mariah Associates Inc., Laramie, Wyoming, by HydroGeo, Inc., Crested Butte, Colorado. 17 pp.

Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA). 2014. The Fundamentals of Successful Well Collision Avoidance Management. ISCWSA Collision Avoidance Workgroup. January 8. Available online: http://www.iscwsa.net/index.php/iscwsa-doc/.

Jorgensen Engineering Land Survey, PC and Hinkley Consulting (Jorgensen). 1994. Big Piney/Marbleton Level II Water Supply Report. Prepared for Wyoming Water Development Commission.

Law, B., and Johnson, R.C. 1989. Structural and stratigraphic framework of the Pinedale Anticline, Wyoming, and the Multiwell Experiment Site, Colorado. Chapter B in Law, B.E., and Spencer, C.W., eds., Geology of tight gas reservoirs in the Pinedale Anticline area, Wyoming, and at the Multiwell Experiment Site, Colorado: U.S. Geological Survey Bulletin 1886, 11 p.

Law, B.E. 1996. Southwestern Wyoming province (037), in D.L. Gautier, G.L. Dolton, K.I. Takahashi, and K.L. Varnes, eds. 1995. National assessment of United States oil and gas resources—results, methodology, and supporting data: U.S. Geological Survey Digital Data Series DDS-30, Release 2, 1 CDROM.

Linn Energy. 2013. Linn Operation, Inc. – Required Annual Jonah Record of Decision (ROD) Water Well Filing. Letter Report submitted to Wyoming Department of Environmental Quality. January 21.

Linn Energy. 2014. Fresh water usage and water injection volumes for the Jonah Field. 2013 Depletions report submitted to the Bureau of Land Management and ICF. June 19.

Martin, L.J. 1996. Geohydrology of Tertiary rocks in the Green River structural basin in Wyoming, Utah, and Colorado: U.S. Geological Survey Water-Resources Investigations Report 92-4164, 43 p.

Montague, J.A. and G.F. Pinder. 2015. Potential of hydraulically induced fractures to communicate with existing wellbores. Water Resources Research 51: 8303-8315. doi: 10.1002/2014WR016771.

Montgomery, S.L., and J.W. Robinson. 1997. Jonah Field, Sublette County Wyoming: Gas Production from Overpressured Upper Cretaceous Lance Sandstones of the Green River Basin. American Association of Petroleum Geologists Bulletin V. 81 No. 7 July 1997, pp. 1049-1062.

Myers, Tom. 2012. Potential Contaminant Pathways from Hydraulically Fractured Shale to Aquifers. *Ground Water*, 50:6, 872-882.

National Drought Mitigation Center. 2014a. United States Drought Monitor, Tabular Data Archive. Available online: http://droughtmonitor.unl.edu/MapsAndData/DataTables.aspx?WY.

National Drought Mitigation Center. 2014b. U.S. Drought Monitor Classification Scheme. Available online: http://droughtmonitor.unl.edu/AboutUs/ClassificationScheme.aspx.

Nelson, P.H., S.M. Ewald, S.L. Santus, and P.K. Trainor. 2010. Gas, oil, and water production from Jonah, Pinedale, Greater Wamsutter, and Stagecoach Draw fields in the Greater Green River Basin, Wyoming: U.S. Geological Survey Open-File Report 2009–1290, 5 plates, pamphlet 19 p.

Phillips, Randy. 2013a. Personal communication regarding the recovery of hydraulic fracturing fluids. Email dated February 27 to ICF and BLM.

Phillips, Randy. 2013b. Jonah well logs. Email from Randy Phillips (Encana) to Alan Rabinoff (ICF) containing open hole well logs. August 5.

Phillips, Randy. 2013c. NPL – Lanced Produced Water Analyses. Email from Randy Phillips (Encana) to John Priecko and Alan Rabinoff (ICF) containing water analyses for produced water from the Lance formation for several wells in the NPL Project Area. August 20.

Prichard, D., Anderson, J., Correll, C., Fogg, J., Gebhardt, K., Krapf, R., Leonard, S., Mitchell, B., and Staats, J. 1998. *Riparian Area Management: A User Guide to Assessing Proper Functioning Conditions and the Supporting Science for Lotic Areas.* TR 1737-15, Bureau of Land Management, Denver, Colorado.

Rieman, Richard E. 2006. Deep Freshwater Aquifers in the Jonah and Pinedale Anticline. Memo.

Roehler, H.W., 1992. Introduction to Greater Green River Basin Geology, Physiography, and History of Investigations. U.S. Geological Society Professional Paper 1506-A.

Rozell, Daniel J., and Sheldon J. Reaven. 2012. Water Pollution Risk Associated with Natural Gas Extraction from the Marcellus Shale. Risk Analysis, 32:8.

Shanley, K.W. 2004. Fluvial Reservoir Description for a giant low permeability gas field: Jonah Field, Green River Basin USA, in Jonah Field: Case Study of a Giant Tight-Gas Fluvial Reservoir, J.W. Robinson and K.W. Shanley, eds. AAPG Studies in Geology 52 and Rocky Mountain Association of Geologists 2004 Guidebook.

Siguaw, S.G., and D.C. Friend. 2004. Extending the Southwest Limits of the Jonah Field: Using High-quality 3-D Seismic Data to Improve the Structural Definition, in Jonah Field: Case Study of a Giant Tight-Gas Fluvial Reservoir, J.W. Robinson and K.W. Shanley, eds. AAPG Studies in Geology 52 and Rocky Mountain Association of Geologists 2004 Guidebook.

Sublette County Conservation District (SCCD). 2014. Discussing Hydrocarbon-related Detections in Groundwater, Associated with the Pinedale Anticline Project Area Groundwater Monitoring Program conducted by the Sublette County Conservation District, 2004 through 2012. Available at: http://www.sublettecd.com/pid/58/water-quality_quantity.aspx

Trihydro 2011. Groundwater Characterization. Normally Pressured Lance Gas Development Project, Sublette County, Wyoming. Prepared for Jonah Energy Oil & Gas (USA), Inc. by Trihydro Corporation, Laramie, Wyoming. 29 pp.

Trihydro. 2013. 2012 Annual Water Sampling, Normally Pressured Lance Gas Development Project, Sublette County, Wyoming. Prepared for Jonah Energy Oil & Gas (USA), Inc. by Trihydro Corporation, Laramie, Wyoming. 448 pp.

Trihydro. 2014a. 2013 Annual Water Sampling, Normally Pressured Lance Natural Gas Development Project, Sublette County, Wyoming. Prepared for Jonah Energy Oil & Gas (USA), Inc. by Trihydro Corporation, Laramie, Wyoming.

Trihydro. 2014b. 2014 Annual Water Sampling, Normally Pressured Lance Natural Gas Development Project, Sublette County, Wyoming. Prepared for Jonah Energy LLC by Trihydro Corporation, Laramie, Wyoming.

Trihydro. 2014c. Sampling and Analysis Plan, Annual Water Well Sampling Program for the Normally Pressured Lance Natural Gas Development Project, Sublette County, Wyoming. Prepared for Jonah Energy LLC by Trihydro Corporation, Laramie, Wyoming.

U.S. Climate Data. 2015a. Climate – Big Piney – Wyoming. Available online: http://www.usclimatedata.com/climate/big-piney/wyoming/united-states/uswy0018. Accessed: October 13, 2015.

U.S. Climate Data. 2015b. Climate-Pinedale-Wyoming. Available online: http://www.usclimatedata.com/climate/pinedale/wyoming/united-states/uswy0134. Accessed: October 13, 2015.

U.S. Climate Data. 2015c. Climate-Farson-Wyoming. Available online: http://www.usclimatedata.com/climate/farson/wyoming/united-states/uswy0058. Accessed: October 13, 2015.

United States Geological Survey (USGS). 2013. Groundwater well inventory and assessment in the area of the proposed Normally Pressured Lance natural gas development project, Green River Basin, Wyoming. 2012: U.S. Geological Survey Data Series 770, 27p. Available online: http://pubs.usgs.gov/770/.

United States Geological Survey (USGS). 2015a. Hydrogeology, groundwater levels, and generalized potentiometric-surface map of the Green River Basin lower Tertiary aquifer system, 2010–14, in the northern Green River structural basin, Wyoming: U.S. Geological Survey Scientific Investigations Report 2015–5090, 33 p., http://dx.doi.org/10.3133/sir20155090. Available online: http://pubs.er.usgs.gov/publication/sir20155090.

US Geological Survey (USGS). 2015b. USGS Watershed Boundary Dataset. Available online: http://nhd.usgs.gov/. Accessed November 2015.

US Geological Survey (USGS). 2010. USGS Watershed Boundary Dataset. Available online: http://nhd.usgs.gov/wbd.html. Accessed October 2012.

Warner, Edward M. 2000. Structural geology and pressure compartmentalization of Jonah Field based on 3-D seismic data and subsurface geology, Sublette County, Wyoming. The Mountain Geologist 37(1): 15-30.

Warner, N.R., R.B. Jackson, T.H. Darrah, S.G. Osborn, A. Down, K. Zhao, A. White, and A. Vengosh. 2012. Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. *PNAS,* 109:30, 11961-11966.

Warpinski, N.R., 2011. Measurements and Observations of Fracture Height Growth. EPA Hydraulic Fracturing Workshop. Technical Presentation Session 6. Available online: http://www2.epa.gov/sites/production/files/documents/measurementandobservationsoffractureheightgrowth.pdf.

Welder, G.E., 1968. Ground-Water Reconnaissance of the Green River Basin, Southwestern Wyoming, U.S Geological Survey Hydrologic Investigations Atlas HA-290.

Whiticar, M.J. 1999. Carbon and hydrogen isotope systematic of bacterial formation and oxidation of methane. Chem Geol. 161, 291-314.

Winterfeld, G.F. 2011. Geological and Paleontological Resources – Final Technical Memorandum: Normally Pressured Lance Natural Gas Development Project. Prepared for BLM. 28 pp.

WWC Engineering, AECOM, and ERO Resources Corp. 2010. GRB Plan, Prepared for the Wyoming Water Development Commission Basin Planning Program. December. 189 pp.

Wyoming Department of Environmental Quality (WQED). 2007. Surface Water Quality Standards, Certified April 25 2007. Available online: http://deq.wyoming.gov/wqd/surface-water-quality-standards/.

Wyoming Department of Environmental Quality (WDEQ). 2013. Fact Sheets, Soil and Groundwater Cleanup Level Tables. December 11. Available online: http://deq.state.wy.us/volremedi/downloads/Current%20Fact%20Sheets/140407_cleanup_table.pdf.

Wyoming Department of Environmental Quality (WDEQ). 2014. Wyoming Water Quality Assessment and Impaired Waters List (2014 Integrated 305(b) and 303(d) Report).

Wyoming Department of Environmental Quality (WDEQ). 2015. Water Quality Rules and Regulations, Chapter 8. Quality Standards for Wyoming Groundwater. Available online: http://soswy.state.wy.us/Rules/RULES/9929.pdf.

Wyoming Oil and Gas Conservation Commission (WOGCC). 2003. Report of the Commission. Docket No. 84-2003. Cause No. 1. Order No. 1.

Wyoming Oil and Gas Conservation Commission (WOGCC). 2008. Chapter 3. Operational Rules, Drilling Rules. Wyoming Oil and Gas Regulations. Available online: http://soswy.state.wy.us/RULES/rules/6913.pdf.

Wyoming Oil and Gas Conservation Commission (WOGCC). 2014. Wyoming Oil and Gas Conservation Commission, Wells Database. Available online: http://wogcc.state.wy.us/.

Wyoming Oil and Gas Conservation Commission (WOGCC). 2015. Data obtained from the computerized records of the Wyoming Oil and Gas Conservation Commission available via the Internet at their website: http://wogcc.state.wy.us. Compiled and maintained by the Wyoming Oil and Gas Conservation Commission. Casper, Wyoming. Accessed September 9, 2015.

Wyoming State Engineer's Office (SEO). 2011. Regulations and Instructions Part III, Water Well Minimum Construction Standards. Available online: https://sites.google.com/a/wyo.gov/seo/regulations-instructions#Ground.

Wyoming State Engineer's Office (SEO). 2014. Search for a Water Right – e-Permit Database. Available online: http://seoweb.wyo.gov/e-Permit. Search conducted July, 2014.

Wyoming State Geological Survey (WSGS). 2010. GRB Water Plan II Groundwater Study Level 1 (2007–2009). Executive Summary.

Wyoming Water Development Commission (WWDC) and University of Wyoming. 1990. Wyoming Water Atlas, a Wyoming Centennial Publication. Ostresh, L.M. et al. 1990. Wyoming Water Atlas. Available online: http://library.wrds.uwyo.edu/wrp/90-02/index.html.

Wyoming Water Development Commission (WWDC). 2014. Upper Green Watershed Study. Level I. Sublette County Conservation District. November 2014. 776 pp.

Wyoming Water Development Office. 2012. Green River Basin Water Plan, Technical Memoranda. Green River Basin Plan, Surface Water Quality. Prepared by Jake Strohman, States West Water Resources Corporation. Available online: http://waterplan.state.wy.us/plan/green/techmemos/swquality.html.

ATTACHMENT A. Groundwater Flow Model and Hydrogeologic Impact Assessment - Jonah Infill Drilling Project

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Surface & Groundwater Hydrology (final version)

GROUNDWATER FLOW MODEL AND HYDROLOGIC IMPACT ASSESSMENT

JONAH INFILL DRILLING PROJECT

Prepared for
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February 2004

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GROUNDWATER FLOW MODEL AND HYDROLOGIC IMPACT ASSESSMENT, JONAH INFILL DRILLING PROJECT

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February 2004

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1.0 OVERVIEW

In conjunction with the Bureau of Land Management (BLM), TRC Mariah Associates Inc. (TRC Mariah) is preparing a third party environmental impact statement (EIS) for the proposed Jonah Infill Drilling Project (Project) located approximately 32 miles southeast of Pinedale, Wyoming (Map 1.1). TRC Mariah contracted HydroGeo, Inc. (HydroGeo) to complete a water depletion and hydrologic impact analysis to support the EIS. HydroGeo analyzed the potential direct hydrological impacts of the proposed Project by using a numerical groundwater flow model.

A numerical groundwater flow model was developed for the Project using the computer code MODFLOW. The model was designed to simulate the regional effect of combined groundwater pumping from the Green River/Wasatch aquifer system for the duration of project development (12.4 to 41.3 years). Model results were used to assess the potential direct impacts of proposed Project groundwater pumping to surface and groundwater resources.

MODFLOW is a block-centered, finite difference model that was developed by the U.S. Geologic Survey to model groundwater flow and the interaction between groundwater and surface water (McDonald and Harbaugh 1988). The MODFLOW model is widely accepted by federal and state regulatory agencies. Input and output from the groundwater flow was managed using Groundwater Vistas, a graphical interface for MODFLOW that facilitates the development of model files, contouring, and analysis of model results.

The Project groundwater flow model (Jonah Infill Model) was developed in two steps:

1. a steady-state model of the existing condition was prepared, and
2. a predictive model for the proposed Project was prepared.

The steady-state model was developed to simulate the hydrologic regime prior to oil and gas development. The steady-state model served as the basis for predictive model runs and was calibrated to simulate historic data. The calibrated steady-state model was used to predict potential future impacts from proposed Project-required freshwater pumping operations. The Jonah Infill Model was based on the conceptual hydrogeologic model developed for past

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Figures in this Attachment Are Unavailable

Map 1.1 Jonah Infill Drilling Project Location, Sublette County, Wyoming, 2004.

hydrogeologic studies (Dynamac Corporation [Dynamac] 2002) and recent data compiled by the BLM, TRC Mariah, and HydroGeo.

This report documents the Jonah Infill Model setup, hydrologic input parameters, and descriptions of the evaluated pumping scenarios, and includes a discussion of the modeling results and impact analysis.

2.0 DESCRIPTION OF MODEL DOMAIN AND INPUT PARAMETERS

2.1 INPUT FILES

The following MODFLOW packages (U.S. Geologic Survey 1996) were used in developing the Jonah Infill Model:

- BAS (basic package),
- BCF (block-centered flow package),
- OC (output control package),
- RCH (recharge package),
- PCG2 (solver package), and
- WEL (well package).

2.2 MODEL DOMAIN AND GRID

The Jonah Infill Model domain encompasses an area of approximately 1,400 square miles (3,626 square km) (Map 2.1). The model grid is oriented in a north/south direction. The southern model boundary extends from the Green River north of La Barge, Wyoming, east to the Big Sandy Reservoir. The western model boundary runs along the Green River north to the confluence with the New Fork River. The northern model boundary follows the New Fork River to its confluence with the East Fork River and then follows the East Fork River. The eastern model boundary follows the East Fork River and the Big Sandy River to Big Sandy Reservoir. The model grid is divided into 119 columns and 106 rows representing distances of approximately 41 miles (66 km) and 34 miles (55 km), respectively. Cell spacing is 250 m

Map 2.1 Model Domain and Boundary, Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

GROUNDWATER FLOW MODEL AND HYDROLOGIC IMPACT ASSESSMENT, JONAH INFILL DRILLING PROJECT

Prepared for

TRC Mariah Associates Inc.
Laramie, Wyoming

By

HydroGeo, Inc.
Crested Butte, Colorado

February 2004

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2.4 MODEL PARAMETERS

2.4.1 Hydraulic Conductivity

The hydraulic conductivity used in the Jonah Infill Model ranges from 1.6 to 9.8 ft/day (≈0.5 to 3.0 m/day). The hydraulic conductivity of the upper model layer ranges from 5.0 to 9.8 ft/day (≈1.5 to 3.0 m/day) and is depicted on Map 2.2. The highest hydraulic conductivity is assigned to the constant head cells along the rivers to simulate the alluvial aquifer. Hydraulic conductivity decreases towards the center of the model domain.

The lowest hydraulic conductivity is applied to the lower layer of the model to represent the deeper part of the Wasatch aquifer. The hydraulic conductivity in the lower model layer was assumed to be uniform at 1.6 ft/day (≈0.5 m/day). This hydraulic conductivity is similar to the conductivity applied by Martin, as described in Chafin and Kimball (1992). Martin simulated a value of 6.5 ft/day (≈2.0 m/day) for the upper few hundred feet of the Wasatch Formation in most of the northern Green River Basin and a hydraulic conductivity of 0.9 ft/day (≈0.3 m/day) for the deeper part of the Wasatch Formation (Chafin and Kimball 1992). Hydraulic conductivity is isotropic in a horizontal direction throughout the model ($K_x = K_y$).

2.4.2 Specific Yield

A uniform specific yield (S_y) of 0.06 was used for the entire aquifer. This is a typical specific yield for an unconfined sandstone\siltstone type aquifer (Freeze and Cherry 1979).

2.4.3 Recharge

Typical recharge rates for semi-arid areas range from 5% to 10% of annual precipitation. The average precipitation in the Project area is about 10 inches (25.4 cm) per year (Lowham et al. 1985). A conservative uniform recharge rate of 5% (0.5 inch [≈1.3 cm]) per year was applied over the extent of the model domain.

Map 2.2 Assigned Hydraulic Conductivities, Upper Model Layer, Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

3.0 STARTING HEADS

A steady-state model, assuming no discharge from the pumping wells was used to develop starting heads for the pumping simulation. The steady-state potentiometric surface is displayed in Map 3.1.

4.0 CALIBRATION

A limited steady-state calibration based on data presented in the Dynamac report *Attachment E: Final PAPA Potentiometric Surface Map* (Dynamac 2002) was performed. The southern half of the PAPA study area overlaps the northern half of the model domain. Three wells on the PAPA map fall within the model boundaries. These wells were plotted and are shown on Map 2.1, and pertinent data are summarized in Table 4.1.

Four additional wells within the model domain (P131008W, P111928W, P9349P, P68609W) were inventoried (Dynamac 2002), but were not used in the creation of the potentiometric map, or for the calibration of the Jonah Infill Model. These four wells are in proximity to each other; however, they exhibit head differences of up to 64 m (≈210 ft). Since it could not be determined whether the head difference is due to a perched aquifer or other causes, these wells were not used in the calibration of the model.

Table 4.1 Calibration Target Heads, Jonah Infill Project, Sublette County, Wyoming, 2004.

Well Permit	Measured Head (m)	Model Head (m)	Residual (m)
P132627W	2,106	2,104.42	1.58
P107650W	2,112	2,114.40	-2.40
P113481W	2,114	2,116.14	-2.14

Map 3.1 Steady-state Potentiometric Surface Map (Contour Interval 10 m), Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

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Additional wells inventoried by the Wyoming State Engineer (2004) were also examined for use in the calibration of the steady-state potentiometric surface. However, information provided for those wells was not accurate enough to be useful for model calibration. Specifically, well location data were only provided to quarter-quarter section, so exact locations and elevations could not be mapped. No pumping data from area wells were available so a transient calibration could not be completed for this study.

5.0 PUMPING SIMULATION

A total of 25 pumping wells were simulated in the model scenarios (see Map 2.1). These 25 wells are existing wells inside the Project area that are currently used by oil and gas companies for project purposes (e.g., drilling, completion). A summary of the data for these wells is listed in Table 5.1. The northings and eastings have been estimated on the map, based on the quarter-quarter section of the well location. All wells were simulated as pumping from the upper model layer (i.e., all wells are assumed to pump from the upper 500 ft [≈152 m] of the aquifer). Well depth and depth to water are reported for some of the existing wells (Wyoming State Engineer 2004) and average well depth is about 500 ft (≈152 m) (Table 5.1).

An additional 16 water wells (estimated to be approximately 500 ft in depth) may be drilled within the Project area during development, but the locations of the new wells have not been determined. The addition of 16 new wells does not change the overall pumping requirements for the Project (as modeled) and would likely have little effect on the geometry and extent of the drawdown cone.

5.1 MODELED SCENARIOS

Three pumping scenarios were performed for this modeling effort. For all three scenarios it was assumed that all wells would produce at the same rate for the same time period.

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Table 5.1 Pumping Wells, Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

		Location[2]								
Permit #	Status[1]	T	R	S	Qtr Qtr	Applicant	Facility Name	Northing	Easting	Wet Well Depth[3]
P136076W	GST	28N	108W	4	NESW	McMurry Oil Co., BLM	Jonah No. 1-4W	607004	4698258	450
P131932W	GST	28N	108W	7	NWNE	McMurry Oil Co., BLM	Jonah Federal 2-7W	604442	4697488	525
P136073W	GST	28N	109W	13	NENE	BLM, McMurry Oil Co.	Yellow Point 1-13W	603053	4695877	425
P112728W	GSE	28N	109W	14	NENE	BLM, BP America Production Co.	Corona #2-14 WSW	601460	4695884	723
P130677W	GSE	28N	109W	23	SWNE	Forest Oil Corporation	BLM Federal #23-22 Water Source Well	601274	4694078	
P126228W	GSE	29N	107W	18	SWSW	BLM, Amoco Production Co.	Cabrito Unit #13-18	610782	4703697	
P149405W	GST	29N	107W	19	SWSW	McMurry Oil Co. BLM	Cabrito #13-19 W	610803	4702102	540
P120843W	GST	29N	107W	20	SWNW	BLM, BP America Production Co.	Cabrito Unit #5-20 Water Well	612398	4702937	478
P112727W	GSE	29N	107W	31	NENW	BLM, BP America Production Co.	Cabrito #3-31 WSW	611062	4699893	585
P106042W	UNA	29N	108W	11	SWNE	BLM, Anshutz Exploration Corp.	Sand Draw #7-11 (W)	608319	4706042	455
P133368W	GSE	29N	108W	15	SWSE	Amoco Production	Stud Horse Butte #15-15	606742	4703665	
P120836W	GSE	29N	108W	16	SWSE	Wyoming State Board of Land Commissioners, Amoco Production Co.	Jonah Water Supply Well #1	605124	4703651	
P118352W	UNA	29N	108W	20	SESE	BLM, BP America Production Co.	Stud Horse Butte #1	603756	4702028	535
P105051W	UNA	29N	108W	21	SWSE	BLM, Western Gas Resources Inc.	Stud Horse Butte #15-21 W	605155	4702054	490
P104193W	UNA	29N	108W	23	SWSW	Western Gas Resources Inc.	Stud Horse Butte #1	607577	4702080	575
P106093W	UNA	29N	108W	24	SWSE	BLM, Ultra Petroleum	Stud Horse Butte #15-24 WW #1	609994	4702094	510
P134841W	GST	29N	108W	26	NESW	McMurry Oil Co., BLM	Stud Horse Butte #11-26 W	607803	4700675	520
P131350W	GSE	29N	108W	26	SENE	BLM, Amoco Production Co.	Jonah Warehouse Yard-Water Well	608607	4701279	
P103561W	UNA	29N	108W	27	SWSW	BLM, McMurry Oil Co.	Stud Horse Butte #13-27 W	606010	4700455	485
P136074W	GST	29N	108W	29	NESW	BLM, McMurry OIL CO.	Stud Horse Butte #11-29 W	602986	4700618	505
P127221W	GSE	29N	108W	30	SENE	Amoco Production Co., BLM	Corona Unit 1-30 Water Well	602223	4701188	
P149403W	GST	29N	108W	32	SWSW	McMurry Oil Co., BLM	Stud Horse Butte #13-32 W	602817	4698800	420
P130709W	GST	29N	108W	34	SENE	BLM, McMurry Oil Co.	Stud Horse Butte #8-34 W	607040	4699653	620
P148650W	GSI	29N	108W	34	SESE	EnCana Oil & Gas (USA) Inc., BLM	Stud Horse Butte #16-34 W	607040	4698849	--
P150264W	GSI	29N	108W	36	NENW	Frank S. Virden	Scutter Bun #1	609449	4699893	--

1 T = township; R = range; S = section.
2 Status:
GSE = good standing permitted time limits have been extended
GSI = good standing incomplete; required notices not received; not yet expired
GST = good standing
UNA = unadjudicated
3 Well depth below static water table.

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Modeled scenarios included the following.

Scenario 1: Simulate freshwater pumping to accommodate a development drilling rate of 75 wells per year for a period of 41.3 years (requirements for development of 3,100 natural gas wells).

Scenario 2: Simulate freshwater pumping to accommodate a development drilling rate of 150 wells per year for a period of 20.7 years (requirements for development of 3,100 natural gas wells).

Scenario 3: Simulated freshwater pumping to accommodate a development drilling rate of 250 wells per year for a period of 12.4 years (requirements for development of 3,100 natural gas wells).

A summary of the input data for each pumping scenario is presented in Table 5.2.

5.2 STRESS PERIODS

For each model scenario, two stress periods were used; the first one simulates pumping from the Green River/Wasatch aquifer for the duration of the drilling program (i.e., 41.3 years for Scenario 1; 20.7 years for Scenario 2; and 12.4 years for Scenario 3). The second stress period simulates recovery for 10 years after pumping has ended. The pumping stress period was divided into 120 time steps and the recovery period was divided into 100 time steps.

Table 5.2 Summary of Pumping Scenarios, Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

Scenario	No. of Gas Wells (per year)	Water Need per Gas Well (acre-feet)	Water Need for All Gas Wells (acre-feet/year)	Length of Drilling Program (years)	No. of Pumping Wells	Water Per Pumping Well (acre-feet/year)	Water Per Pumping Well (gpm)
1	75	4.9	367.5	41.3	25	14.7	9.1
2	150	4.9	735.0	20.7	25	29.4	18.2
3	250	4.9	1,225.0	12.4	25	49.0	30.4

6.0 MODEL OUTPUT

6.1 RESULTS

Full recovery is defined as the point in time when no drawdown greater than or equal to 1.6 ft (≈0.5 m) exists. The approximate length of time in years to reach full recovery after the end of pumping is presented in Table 6.1. Contour maps of drawdown were prepared for each model scenario at the end of the pumping stress period and are presented in Maps 6.1, 6.2, and 6.3.

6.2 SENSITIVITY ANALYSIS

Hydraulic conductivity was decreased by one order of magnitude to a range from 0.16 to 0.98 ft/day (≈0.05 to 0.30 m/day) for the entire aquifer in order to test the sensitivity of the model to changes in hydraulic conductivity. Smaller hydraulic conductivity values create a lower transmissivity and lead to a larger drawdown from pumping wells. The sensitivity analysis model was run using the most aggressive pumping scenario (Scenario 3).

The drawdown cone resulting from the sensitivity analysis is shown in Map 6.4. The sensitivity analysis drawdown results at the Project boundary were very similar to modeled results in Scenario 3 (see Map 6.3). The drawdown closer to the pumping wells was larger in the sensitivity analysis than in Scenario 3. The results of this analysis indicate that the model is not very sensitive to variations in hydraulic conductivity, particularly in the area at the Project boundary. Sensitivity analyses for specific yield and recharge were not completed because the model values are conservative.

Table 6.1 Modeled Recovery Time, Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

Scenario	Years to Full Recovery After Pumping Ends	Years to Full Recovery from Start of Drilling Program
1	0.5	42
2	4.0	25
3	6.0	18

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Map 6.1 Scenario 1 - Projected Drawdown after 41.3 Years of Pumping (Contour Interval 0.5 m), Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

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Map 6.2 Scenario 2 - Projected Drawdown after 20.7 Years of Pumping (Contour Interval 0.5 m), Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

Map 6.3 Scenario 3 - Projected Drawdown after 12.4 Years of Pumping (Contour Interval 0.5 m), Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

Map 6.4 Sensitivity Analysis Drawdown using Lowered Hydraulic Conductivity (Contour Interval 0.5 m), Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

7.0 MODELING RESULTS AND IMPACT ANALYSIS

Based on the results of the modeling, a 0.5 m (≈1.6 ft) drawdown cone caused by the proposed freshwater pumping will extend only slightly beyond the Project area, even for the most aggressive development, (Scenario 3, 250 gas wells per year). Water levels in water wells within the modeled drawdown cone area may be lowered due to the proposed pumping, particularly in those wells located near the Project water supply wells. However, the groundwater level in the wells should recover rapidly after Project pumping ceases. The model results show that the recovery of the groundwater table will be rapid, ranging from 0.5 to 6 years (see Table 6.1), depending on the pumping scenario. Since seasonal fluctuations in groundwater levels are typically greater than 0.5 m (≈1.6 ft), it would be difficult to distinguish between seasonal effects and pumping effects. As a result, no measurable impacts to surface or groundwater resources outside the modeled drawdown cone are expected.

The 25 modeled pumping wells should be able to sustain the proposed pumping rates for the 250 gas wells per year development scenario. However, the possibility exists that some wells may not be completed in the Green River/Wasatch aquifer, but only in a perched water-bearing zone and, therefore, may not produce as expected. Groundwater quality will not likely be impacted as a result of freshwater pumping.

It should be noted, that the Jonah Infill Model is a large-scale model with limited data available for calibration. Possible variations in well productions due to small-scale variations in the vicinity of one or several water wells cannot be predicted. Well depths for all existing wells used in the model are not available. Local variations in hydraulic conductivity or specific yield may also influence and alter the modeled outcome, although the sensitivity analysis indicates that minor changes in hydraulic conductivity values will not have much effect.

8.0 RECOMMENDATIONS

Monitoring water levels in selected wells within and outside the Project area prior to and during Project operations is recommended to confirm the modeled results. The model could also be periodically recalibrated using the new monitoring data to enhance the model's predictive accuracy.

9.0 REFERENCES

Chafin, T. Daniel, and B.A., Kimball. 1992. Ground-Water Geochemistry of the near-surface Wasatch Formation, Northern Green River Basin, Sublette County, Wyoming. U.S. Geological Suvey Water-Resources Investigations Report 91-4069.

Dynamac Corporation. 2002. Preliminary Ground Water Characterization Study, Pinedale Anticline Production Area (PAPA), Sublette County, Wyoming. Submitted to Bureau of Land Management, Pinedale Field Office.

Freeze, R.A., and J.A. Cherry. 1979. Groundwater. Prentice Hall.

Lowham, H.W., D.A. Peterson, E.A. Zimmerman, E.H. Ringer, and K.C. Mora. 1985. Hydrology of Area 52, Rocky Mountain Coal Province, Wyoming, Colorado, Idaho, and Utah. U.S. Geological Survey Water Resource Investigations Open File Report 83-761.

McDonald, M., and A. Harbaugh. 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, U.S. Geological Survey Techniques of Water Resource Investigations, Book 6, Chapter A1. 586 pp.

United States Geologic Survey. 1996. Users Documentation for MODFLOW-96 an Update to the U.S. Geological Survey Modular Finite-Difference Ground Water Flow Model. Open File Report 96-485.

Wyoming State Engineer. 2004. Water well database. http://seo.state.wy.us/wrdb/index.aspx.

2.4 MODEL PARAMETERS

2.4.1 Hydraulic Conductivity

The hydraulic conductivity used in the Jonah Infill Model ranges from 1.6 to 9.8 ft/day (≈0.5 to 3.0 m/day). The hydraulic conductivity of the upper model layer ranges from 5.0 to 9.8 ft/day (≈1.5 to 3.0 m/day) and is depicted on Map 2.2. The highest hydraulic conductivity is assigned to the constant head cells along the rivers to simulate the alluvial aquifer. Hydraulic conductivity decreases towards the center of the model domain.

The lowest hydraulic conductivity is applied to the lower layer of the model to represent the deeper part of the Wasatch aquifer. The hydraulic conductivity in the lower model layer was assumed to be uniform at 1.6 ft/day (≈0.5 m/day). This hydraulic conductivity is similar to the conductivity applied by Martin, as described in Chafin and Kimball (1992). Martin simulated a value of 6.5 ft/day (≈2.0 m/day) for the upper few hundred feet of the Wasatch Formation in most of the northern Green River Basin and a hydraulic conductivity of 0.9 ft/day (≈0.3 m/day) for the deeper part of the Wasatch Formation (Chafin and Kimball 1992). Hydraulic conductivity is isotropic in a horizontal direction throughout the model ($K_x = K_y$).

2.4.2 Specific Yield

A uniform specific yield (S_y) of 0.06 was used for the entire aquifer. This is a typical specific yield for an unconfined sandstone\siltstone type aquifer (Freeze and Cherry 1979).

2.4.3 Recharge

Typical recharge rates for semi-arid areas range from 5% to 10% of annual precipitation. The average precipitation in the Project area is about 10 inches (25.4 cm) per year (Lowham et al. 1985). A conservative uniform recharge rate of 5% (0.5 inch [≈1.3 cm]) per year was applied over the extent of the model domain.

Map 2.2 Assigned Hydraulic Conductivities, Upper Model Layer, Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

3.0 STARTING HEADS

A steady-state model, assuming no discharge from the pumping wells was used to develop starting heads for the pumping simulation. The steady-state potentiometric surface is displayed in Map 3.1.

4.0 CALIBRATION

A limited steady-state calibration based on data presented in the Dynamac report *Attachment E: Final PAPA Potentiometric Surface Map* (Dynamac 2002) was performed. The southern half of the PAPA study area overlaps the northern half of the model domain. Three wells on the PAPA map fall within the model boundaries. These wells were plotted and are shown on Map 2.1, and pertinent data are summarized in Table 4.1.

Four additional wells within the model domain (P131008W, P111928W, P9349P, P68609W) were inventoried (Dynamac 2002), but were not used in the creation of the potentiometric map, or for the calibration of the Jonah Infill Model. These four wells are in proximity to each other; however, they exhibit head differences of up to 64 m (≈210 ft). Since it could not be determined whether the head difference is due to a perched aquifer or other causes, these wells were not used in the calibration of the model.

Table 4.1 Calibration Target Heads, Jonah Infill Project, Sublette County, Wyoming, 2004.

Well Permit	Measured Head (m)	Model Head (m)	Residual (m)
P132627W	2,106	2,104.42	1.58
P107650W	2,112	2,114.40	-2.40
P113481W	2,114	2,116.14	-2.14

Map 3.1 Steady-state Potentiometric Surface Map (Contour Interval 10 m), Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

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Additional wells inventoried by the Wyoming State Engineer (2004) were also examined for use in the calibration of the steady-state potentiometric surface. However, information provided for those wells was not accurate enough to be useful for model calibration. Specifically, well location data were only provided to quarter-quarter section, so exact locations and elevations could not be mapped. No pumping data from area wells were available so a transient calibration could not be completed for this study.

5.0 PUMPING SIMULATION

A total of 25 pumping wells were simulated in the model scenarios (see Map 2.1). These 25 wells are existing wells inside the Project area that are currently used by oil and gas companies for project purposes (e.g., drilling, completion). A summary of the data for these wells is listed in Table 5.1. The northings and eastings have been estimated on the map, based on the quarter-quarter section of the well location. All wells were simulated as pumping from the upper model layer (i.e., all wells are assumed to pump from the upper 500 ft [≈152 m] of the aquifer). Well depth and depth to water are reported for some of the existing wells (Wyoming State Engineer 2004) and average well depth is about 500 ft (≈152 m) (Table 5.1).

An additional 16 water wells (estimated to be approximately 500 ft in depth) may be drilled within the Project area during development, but the locations of the new wells have not been determined. The addition of 16 new wells does not change the overall pumping requirements for the Project (as modeled) and would likely have little effect on the geometry and extent of the drawdown cone.

5.1 MODELED SCENARIOS

Three pumping scenarios were performed for this modeling effort. For all three scenarios it was assumed that all wells would produce at the same rate for the same time period.

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Table 5.1 Pumping Wells, Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

		Location[2]								
Permit #	Status[1]	T	R	S	Qtr Qtr	Applicant	Facility Name	Northing	Easting	Wet Well Depth[3]
P136076W	GST	28N	108W	4	NESW	McMurry Oil Co., BLM	Jonah No. 1-4W	607004	4698258	450
P131932W	GST	28N	108W	7	NWNE	McMurry Oil Co., BLM	Jonah Federal 2-7W	604442	4697488	525
P136073W	GST	28N	109W	13	NENE	BLM, McMurry Oil Co.	Yellow Point 1-13W	603053	4695877	425
P112728W	GSE	28N	109W	14	NENE	BLM, BP America Production Co.	Corona #2-14 WSW	601460	4695884	723
P130677W	GSE	28N	109W	23	SWNE	Forest Oil Corporation	BLM Federal #23-22 Water Source Well	601274	4694078	
P126228W	GSE	29N	107W	18	SWSW	BLM, Amoco Production Co.	Cabrito Unit #13-18	610782	4703697	
P149405W	GST	29N	107W	19	SWSW	McMurry Oil Co. BLM	Cabrito #13-19 W	610803	4702102	540
P120843W	GST	29N	107W	20	SWNW	BLM, BP America Production Co.	Cabrito Unit #5-20 Water Well	612398	4702937	478
P112727W	GSE	29N	107W	31	NENW	BLM, BP America Production Co.	Cabrito #3-31 WSW	611062	4699893	585
P106042W	UNA	29N	108W	11	SWNE	BLM, Anshutz Exploration Corp.	Sand Draw #7-11 (W)	608319	4706042	455
P133368W	GSE	29N	108W	15	SWSE	Amoco Production	Stud Horse Butte #15-15	606742	4703665	
P120836W	GSE	29N	108W	16	SWSE	Wyoming State Board of Land Commissioners, Amoco Production Co.	Jonah Water Supply Well #1	605124	4703651	
P118352W	UNA	29N	108W	20	SESE	BLM, BP America Production Co.	Stud Horse Butte #1	603756	4702028	535
P105051W	UNA	29N	108W	21	SWSE	BLM, Western Gas Resources Inc.	Stud Horse Butte #15-21 W	605155	4702054	490
P104193W	UNA	29N	108W	23	SWSW	Western Gas Resources Inc.	Stud Horse Butte #1	607577	4702080	575
P106093W	UNA	29N	108W	24	SWSE	BLM, Ultra Petroleum	Stud Horse Butte #15-24 WW #1	609994	4702094	510
P134841W	GST	29N	108W	26	NESW	McMurry Oil Co., BLM	Stud Horse Butte #11-26 W	607803	4700675	520
P131350W	GSE	29N	108W	26	SENE	BLM, Amoco Production Co.	Jonah Warehouse Yard-Water Well	608607	4701279	
P103561W	UNA	29N	108W	27	SWSW	BLM, McMurry Oil Co.	Stud Horse Butte #13-27 W	606010	4700455	485
P136074W	GST	29N	108W	29	NESW	BLM, McMurry OIL CO.	Stud Horse Butte #11-29 W	602986	4700618	505
P127221W	GSE	29N	108W	30	SENE	Amoco Production Co., BLM	Corona Unit 1-30 Water Well	602223	4701188	
P149403W	GST	29N	108W	32	SWSW	McMurry Oil Co., BLM	Stud Horse Butte #13-32 W	602817	4698800	420
P130709W	GST	29N	108W	34	SENE	BLM, McMurry Oil Co.	Stud Horse Butte #8-34 W	607040	4699653	620
P148650W	GSI	29N	108W	34	SESE	EnCana Oil & Gas (USA) Inc., BLM	Stud Horse Butte #16-34 W	607040	4698849	--
P150264W	GSI	29N	108W	36	NENW	Frank S. Virden	Scutter Bun #1	609449	4699893	--

1 T = township; R = range; S = section.
2 Status:
GSE = good standing permitted time limits have been extended
GSI = good standing incomplete; required notices not received; not yet expired
GST = good standing
UNA = unadjudicated
3 Well depth below static water table.

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Modeled scenarios included the following.

Scenario 1: Simulate freshwater pumping to accommodate a development drilling rate of 75 wells per year for a period of 41.3 years (requirements for development of 3,100 natural gas wells).

Scenario 2: Simulate freshwater pumping to accommodate a development drilling rate of 150 wells per year for a period of 20.7 years (requirements for development of 3,100 natural gas wells).

Scenario 3: Simulated freshwater pumping to accommodate a development drilling rate of 250 wells per year for a period of 12.4 years (requirements for development of 3,100 natural gas wells).

A summary of the input data for each pumping scenario is presented in Table 5.2.

5.2 STRESS PERIODS

For each model scenario, two stress periods were used; the first one simulates pumping from the Green River/Wasatch aquifer for the duration of the drilling program (i.e., 41.3 years for Scenario 1; 20.7 years for Scenario 2; and 12.4 years for Scenario 3). The second stress period simulates recovery for 10 years after pumping has ended. The pumping stress period was divided into 120 time steps and the recovery period was divided into 100 time steps.

Table 5.2 Summary of Pumping Scenarios, Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

Scenario	No. of Gas Wells (per year)	Water Need per Gas Well (acre-feet)	Water Need for All Gas Wells (acre-feet/year)	Length of Drilling Program (years)	No. of Pumping Wells	Water Per Pumping Well (acre-feet/year)	Water Per Pumping Well (gpm)
1	75	4.9	367.5	41.3	25	14.7	9.1
2	150	4.9	735.0	20.7	25	29.4	18.2
3	250	4.9	1,225.0	12.4	25	49.0	30.4

6.0 MODEL OUTPUT

6.1 RESULTS

Full recovery is defined as the point in time when no drawdown greater than or equal to 1.6 ft (≈0.5 m) exists. The approximate length of time in years to reach full recovery after the end of pumping is presented in Table 6.1. Contour maps of drawdown were prepared for each model scenario at the end of the pumping stress period and are presented in Maps 6.1, 6.2, and 6.3.

6.2 SENSITIVITY ANALYSIS

Hydraulic conductivity was decreased by one order of magnitude to a range from 0.16 to 0.98 ft/day (≈0.05 to 0.30 m/day) for the entire aquifer in order to test the sensitivity of the model to changes in hydraulic conductivity. Smaller hydraulic conductivity values create a lower transmissivity and lead to a larger drawdown from pumping wells. The sensitivity analysis model was run using the most aggressive pumping scenario (Scenario 3).

The drawdown cone resulting from the sensitivity analysis is shown in Map 6.4. The sensitivity analysis drawdown results at the Project boundary were very similar to modeled results in Scenario 3 (see Map 6.3). The drawdown closer to the pumping wells was larger in the sensitivity analysis than in Scenario 3. The results of this analysis indicate that the model is not very sensitive to variations in hydraulic conductivity, particularly in the area at the Project boundary. Sensitivity analyses for specific yield and recharge were not completed because the model values are conservative.

Table 6.1 Modeled Recovery Time, Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

Scenario	Years to Full Recovery After Pumping Ends	Years to Full Recovery from Start of Drilling Program
1	0.5	42
2	4.0	25
3	6.0	18

Map 6.1 Scenario 1 - Projected Drawdown after 41.3 Years of Pumping (Contour Interval 0.5 m), Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

Map 6.2 Scenario 2 - Projected Drawdown after 20.7 Years of Pumping (Contour Interval 0.5 m), Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

Map 6.3 Scenario 3 - Projected Drawdown after 12.4 Years of Pumping (Contour Interval 0.5 m), Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

Map 6.4 Sensitivity Analysis Drawdown using Lowered Hydraulic Conductivity (Contour Interval 0.5 m), Jonah Infill Drilling Project, Sublette County, Wyoming, 2004.

7.0 MODELING RESULTS AND IMPACT ANALYSIS

Based on the results of the modeling, a 0.5 m (≈1.6 ft) drawdown cone caused by the proposed freshwater pumping will extend only slightly beyond the Project area, even for the most aggressive development, (Scenario 3, 250 gas wells per year). Water levels in water wells within the modeled drawdown cone area may be lowered due to the proposed pumping, particularly in those wells located near the Project water supply wells. However, the groundwater level in the wells should recover rapidly after Project pumping ceases. The model results show that the recovery of the groundwater table will be rapid, ranging from 0.5 to 6 years (see Table 6.1), depending on the pumping scenario. Since seasonal fluctuations in groundwater levels are typically greater than 0.5 m (≈1.6 ft), it would be difficult to distinguish between seasonal effects and pumping effects. As a result, no measurable impacts to surface or groundwater resources outside the modeled drawdown cone are expected.

The 25 modeled pumping wells should be able to sustain the proposed pumping rates for the 250 gas wells per year development scenario. However, the possibility exists that some wells may not be completed in the Green River/Wasatch aquifer, but only in a perched water-bearing zone and, therefore, may not produce as expected. Groundwater quality will not likely be impacted as a result of freshwater pumping.

It should be noted, that the Jonah Infill Model is a large-scale model with limited data available for calibration. Possible variations in well productions due to small-scale variations in the vicinity of one or several water wells cannot be predicted. Well depths for all existing wells used in the model are not available. Local variations in hydraulic conductivity or specific yield may also influence and alter the modeled outcome, although the sensitivity analysis indicates that minor changes in hydraulic conductivity values will not have much effect.

8.0 RECOMMENDATIONS

Monitoring water levels in selected wells within and outside the Project area prior to and during Project operations is recommended to confirm the modeled results. The model could also be periodically recalibrated using the new monitoring data to enhance the model's predictive accuracy.

9.0 REFERENCES

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Dynamac Corporation. 2002. Preliminary Ground Water Characterization Study, Pinedale Anticline Production Area (PAPA), Sublette County, Wyoming. Submitted to Bureau of Land Management, Pinedale Field Office.

Freeze, R.A., and J.A. Cherry. 1979. Groundwater. Prentice Hall.

Lowham, H.W., D.A. Peterson, E.A. Zimmerman, E.H. Ringer, and K.C. Mora. 1985. Hydrology of Area 52, Rocky Mountain Coal Province, Wyoming, Colorado, Idaho, and Utah. U.S. Geological Survey Water Resource Investigations Open File Report 83-761.

McDonald, M., and A. Harbaugh. 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, U.S. Geological Survey Techniques of Water Resource Investigations, Book 6, Chapter A1. 586 pp.

United States Geologic Survey. 1996. Users Documentation for MODFLOW-96 an Update to the U.S. Geological Survey Modular Finite-Difference Ground Water Flow Model. Open File Report 96-485.

Wyoming State Engineer. 2004. Water well database. http://seo.state.wy.us/wrdb/index.aspx.

8.0 RECOMMENDATIONS

Monitoring water levels in selected wells within and outside the Project area prior to and during Project operations is recommended to confirm the modeled results. The model could also be periodically recalibrated using the new monitoring data to enhance the model's predictive accuracy.

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Dynamac Corporation. 2002. Preliminary Ground Water Characterization Study, Pinedale Anticline Production Area (PAPA), Sublette County, Wyoming. Submitted to Bureau of Land Management, Pinedale Field Office.

Freeze, R.A., and J.A. Cherry. 1979. Groundwater. Prentice Hall.

Lowham, H.W., D.A. Peterson, E.A. Zimmerman, B.H. Ringer, and K.C. Mora. 1985. Hydrology of Area 52, Rocky Mountain Coal Province, Wyoming, Colorado, Idaho, and Utah. U.S. Geological Survey Water Resource Investigations Open File Report 83-761.

McDonald, M., and A. Harbaugh. 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, U.S. Geological Survey Techniques of Water Resource Investigations, Book 6, Chapter A1. 586 pp.

United States Geologic Survey. 1996. Users Documentation for MODFLOW-96 an Update to the U.S. Geological Survey Modular Finite-Difference Ground Water Flow Model. Open File Report 96-485.

Wyoming State Engineer. 2004. Water well database. http://seo.state.wy.us/wrdb/index.aspx.

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ATTACHMENT B. Water Supply Wells in and around the Project Area

Table B-1. Water Supply Wells in and Around the NPL Project Area

Map Reference #	Well name (SEO Facility)	SEO Permit No.	Township	Range	Section	Qtr Section	Qtr-Qtr	Trihydro Reference Name	USGS Reference Name/Site Number	Latitude	Longitude	Well Depth (ft bgs)	Static Water Level (ft)	Permitted Use	Primary Aquifer	Notes
Existing Water Supply Wells within the NPL Project Area																
1	Tea Kettle Butte Well	96392W	27	108	2	SE	NWSE	TKB	--	42.34194	109.652675	1573*	840	Stock	Wasatch	SEO indicates the bottom of the water producing zone is 860 feet.
2	Davis Luman Road Water	41168W	27	108	21	SW	NWSW	--	421800109420701	42.299861	109.701889	700*	70*	Stock	Wasatch	
3	Davis Old Road Unit #1 Water	54621W	27	108	27	SE	NWSE	STA	421706109402501	42.285028	109.673528	730*	Flowing	Misc.	Wasatch	Flowing artesian well. Former drilling water supply, no longer used.
58	Midland Well 2011-2	195392W	27	108	36	NE	SWNE	--	--	42.272683	109.63505	400*	Flowing	Stock	Wasatch	Artesian well.
4	12 Mile Road Well #4519	51217W	27	109	7	NW	SENW	--	422016109511001	42.337833	109.852889	483	215*	Stock	Wasatch	
59	Davis Sugar Loaf Unit #1 Water	41012W	27	109	7	NW	NENW	--	--	42.33795	109.85351	200*	80*	Misc.	Wasatch	
5	Radio Tower 1-8 WW	180214W	28	107	8	NE	NENE	--	422513109353401	42.420167	109.592694	587*	110	Misc.	Wasatch	
6	--	--	28	107	8	NW	NWNW	Err1/NP2	422408109350001	42.405056	109.590694	900	Flowing	Stock	Wasatch	Flowing artesian well.
7	14cbd02	--	28	108	14	SW	NWSW	NP4	422357109394801	42.399083	109.663194	128.5	--	Stock	Laney	
8	Jonah Well #1	147913W	28	108	16	SE	SESE	--	422351109411902	42.397472	109.688611	363	110*	Stock	Wasatch	
9	--	--	28	108	16	SE	SESE	--	422351109411901	42.397417	109.688611	299.13	--	Stock	Wasatch	Old well; abandoned.
10	Sagebrush Well	180487W	28	108	17	SE	SESE	--	--	--	--	--	--	Stock	Wasatch	
11	Boundary #4645	51229W	28	108	25	NW	NENW	--	422245109383001	42.379222	109.641722	1042*	Flowing	Stock	Wasatch	Flowing artesian well.
12	Hacienda Federal No. 5-29W	135634W	28	108	29	NW	SWNW	--	--	--	--	900*-	--	Misc.	Wasatch	Former drilling water supply, no longer used.
13	Wild Horse Reservoir Well	180486W	28	108	30	SE	NESE	--	--	--	--	--	--	Stock	Wasatch	
14	Erramouspe Well	10497P	28	108	33	NW	NWNW	--	28-108-33bb01	42.366667	109.702111	160	30*	Stock	Wasatch	
15	Bloom Well	9347P	28	109	16	NW	SWNW	P9347	422431109490001	42.408583	109.816528	75*	30*	Stock	Laney	Trihydro shows well as Alluvial
16	Stanley Energy #1 Water Well	107042W	28	109	22	NE	NWNE	--	--	--	--	673*	75*	Misc.	Wasatch	Former drilling water supply, no longer used.
17	Dry Lakes Well #353	9373P	28	109	23	NW	SWNW	--	28-109-23bcc01	42.391222	109.781556	218	100*	Stock	Wasatch	
18	Yellow Point No. 2-24W (Luman Compressor Station)	136075W	28	109	24	NE	SWNE	--	--	--	--	753*	250*	Misc.	Wasatch	Former drilling water supply, no longer used.
19	Horse Trap Well 4462	36203W	28	109	25	SW	NESW	--	422221109452701	42.3725	109.757444	339.61	119*	Stock	Wasatch	
20	Buckhorn #308	9361P	28	109	31	SE	SESE	BHW2	28-109-31dda01	42.356722	109.842694	268	90	Stock	Laney	
21	--	--	28	109	36	SE	SWSE	--	28-109-36dc01	42.3565	109.753556	68	--	Stock	Laney	

Table B-1. Water Supply Wells in and Around the NPL Project Area

Map Reference #	Well name (SEO Facility)	SEO Permit No.	Township	Range	Section	Qtr Section	Qtr-Qtr	Trihydro Reference Name	USGS Reference Name/Site Number	Latitude	Longitude	Well Depth (ft bgs)	Static Water Level (ft)	Permitted Use	Primary Aquifer	Notes
22	Buckhorn Well #313	9360P	28	110	1	SE	NWSE	--	28-110-01dc01	42.429806	109.867722	200*	-1	Stock	Wasatch	
23	Sugar Loaf #389	9619P	28	110	9	NE	SENE	Rees 2	28-110-09ad01	42.422861	109.918528	220	220*	Stock	Wasatch	
24	South Desert #1	8531W	28	110	18	NW	SWNW	BF	28-110-18bc01	42.40625	109.964083	472*	435*	Stock	Wasatch	
25	Antelope #4066	8527W	28	110	22	NW	SENW	PLW	28-110-22bd01	42.388667	109.9075	471*	370*	Stock	Wasatch	
26	CCC Road Well #4083	8522W	28	110	29	NW	NWNW	CCC	--	42.369585	109.968444	500*	300*	Stock	Wasatch	
27	Sugar Loaf Well #390	9620P	28	110	33	NE	SWNE	Rees 1	28-110-33ac01	42.364722	109.922889	420	320*	Stock	Wasatch	
28	Desert	71947W	29	108	18	NW	SWNW	--	--	--	--	225*	105*	Stock	Wasatch	
29	North Alkali Well #2	8434P	29	109	6	NW	SWNW	--	29-109-06bb01	42.520889	109.887528	174	117*	Stock	Wasatch	
30	Granite Wash Well 4461	36202W	29	109	7	SE	NWSE	BRD2	423016109520801	42.504583	109.868833	220*	86*	Stock	Wasatch	
31	Alkali Sun Well #1	176877	29	109	10	NW	NENW	--	--	--	--	23*	16*	Stock	Wasatch	
32	Burma Road Well #2	78016W	29	109	20	SW	SESW	P78016W	422811109514701	42.469444	109.863111	375	285	Stock	Wasatch	
33	Burma Road #1 (Deepened)	8431P	29	109	22	NW	SWNW	--	29-109-22cb01	42.471278	109.826583	480*	295*	Stock	Wasatch	
34	Burma Road Well #3	99087W	29	109	23	SW	SESW	BRD1	422747109481601	42.463028	109.804361	310*	80*	Stock	Wasatch	
35	Alkali Spring #4081	27163W	29	109	30	NW	NENW	--	--	--	--	Spring	0*	Stock	Alluvial	Spring. Source is likely alluvium in stream bed.
36	Alkali Fence Well #1	85836W	29	109	33	SE	SESE	WW1	422618109500401	42.438306	109.834472	254	146	Stock	Wasatch	Windmill.
37	Palomino #5-22W	148371W	29	110	22	NW	SWNW	--	422838109564501	42.477194	109.945833	749.6	220*	Misc.	Wasatch	Former drilling water supply, no longer used.
JIDPA Water Supply Wells within the NPL Project Area (Drilling and Facility Support)																
38	Holmes Federal #5-1W	196053W	27	109	1	NW	SWNW	HOL 5-1W	422054109453601	42.348417	109.760139	630*	200*	Misc.	Wasatch	Artesian Well. Water supply for Jonah drilling.
39	Jonah Federal 4-8WW	181396W	28	108	8	SE	SWSE	--	--	--	--	--	--	Misc.	Wasatch	Water supply for Jonah drilling.
40	Encana Workforce Facility	187090W	28	108	8	SE	SESE	WFF	422446109423501	42.412778	109.709806	1100	358*	Misc.	Wasatch	Jonah Workforce Facility water supply; also used for drilling and reclamation.
41	Plains WSW 32	196049W	28	109	27	SW	SESW	--	--	--	--	510*	150*	Misc.	Wasatch	Water supply for Jonah drilling.
42	SOL 9-36W	195830W	29	109	36	SE	NESE	--	--	--	--	920*	175*	Misc.	Wasatch	Water supply for Jonah drilling.
Wells outside the NPL Project Area used for the Operator's Sampling and Analysis Program (Trihydro 2011, 2013, 2014, 2015)																
43	Emigrant Trail Well 4518	51216W	26	108	10	NW	--	ETW	--	--	--	490	9	Stock	Wasatch	
44	Desert Well #1	10501P	26	109	6	SE	--	DW1	--	--	--	210	124	Stock	Wasatch	
45	North Sublette Meadow Spring	--	27	107	8	SW	SWSW	NSMS/NP3	--	42.326467	109.604021	Spring	--	Stock	Alluvial	Spring.
46	--	--	27	107	--	--	--	PA1	--	--	--	800	Flowing	Stock	Wasatch	Flowing artesian well.

Table B-1. Water Supply Wells in and Around the NPL Project Area

Map Reference #	Well name (SEO Facility)	SEO Permit No.	Township	Range	Section	Qtr Section	Qtr-Qtr	Trihydro Reference Name	USGS Reference Name/Site Number	Latitude	Longitude	Well Depth (ft bgs)	Static Water Level (ft)	Permitted Use	Primary Aquifer	Notes
47	Sagebrush 14-20WW	163911W	27	107	20	SW	SESW	SBW	--	42.297033	109.60159	390*	Flowing	Misc.	Wasatch	Flowing artesian well.
48	Desert Well #2	10502P	27	109	18	SW	SWSW	DW2	--	42.31329	109.856349	205*	28*	Stock	Wasatch	
49	Fear Well #1	6874W	27	110	6	SW	SESW	Fear1	--	42.342749	109.967724	725*	480*	Stock	Wasatch	
50	Oasis Well	10507P	27	110	21	NE	--	Oasis	--	--	--	493	173	Stock	Wasatch	
51	Green River #2	6877W	27	111	24	SW	--	GRW2	--	--	--	732	485	Stock	Wasatch	
52	Reservoir #4638	51222W	28	107	30	SE	--	FEWE	--	--	--	220	31	Stock	Wasatch	
60	JIO Boundary Well	191117W	29	107	34	SE	NWSE	--	--	42.435556	-109.584167	360*	200*	Stock	Wasatch	
53	--	--	29	108	--	--	--	GFW	--	--	--	354	112	Stock	Wasatch	
54	North Alkali Well #1	8432P	29	110	11	SW	--	NA1	--	--	--	91	42	Stock	Alluvial	
55	--	--	29	111	--	--	--	McGinnis 1	--	--	--	400	--	Domestic	Wasatch	Private well.
56	McGinnis #2	140G	29	111	33	--	--	McGinnis 2	--	--	--	155	--	Domestic	Alluvial	Private well.
57	Ross Ridge Well #4310	23979.0W	30	109	19	SW	--	BRD3	--	--	--	555	300	Stock	Wasatch	

Sources: AECOM 2014; AMEC 2014; Trihydro 2011, 2013, 2014a, 2014b; Wyoming SEO 2014.

* = Data obtained from the Wyoming State Engineer's Office (SEO).
"—" = not available

ft feet
ft bgs feet below ground surface

Note: Wyoming SEO records are updated regularly, and permitting information included at the time of this report is based on current information.

ATTACHMENT C. Water Quality Results from Water Wells in and around the NPL Project Area

Table C-1. Water Quality Results from Water Wells in and around the NPL Project Area

Field	Well Name (SEO Facility)	SEO Permit No.	Trihydro Reference Name [Well/Map Reference No.][c]	Data Year	pH (Standard Units)	Total Dissolved Solids (mg/L)	Iron - Total (mg/L)	Iron - Dissolved (mg/L)	Fluoride (mg/L)	Chloride (mg/L)	Methane (mg/L)	DRO (mg/L)	GRO (mg/L)	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	Xylenes (µg/L)
NPL	Alkali Fence Well #1	85836W	WW1 [36]	2011	8.9[e,f,g,i]	2070[e,f,g,h]	0.13	--	--	61.8	ND(0.026)	ND(0.0971)	ND(0.1)	--	ND(1)	--	--
				2013	8.78[e,f,g,i]	2300[e,f,g,h]	0.043[a]	--	3.3[e]	65	0.0047[a]	ND(0.24)	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
	Antelope #4066	8527W	PLW [25]	2012	8.18	1600[e,f,g]	--	0.1[a]	1.4	26	0.0015	ND(0.25)	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2013	8.48	1700[a,e,f,g]	1.8[e,g]	--	1.1	24	ND(0.005)	0.044[a]	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2014	7.08	1640[e,f,g]	--	0.125[a]	1.12[a]	25.8	ND(0.005)	ND(0.0962)	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	CCC Road Well #4083	8522W	CCC [26]	2012	7.99	2300[e,f,g,h]	--	0.052[a]	0.7[a]	16	0.0021	ND(0.24)	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2013	8.25	2300[e,f,g,h]	3.5[e,g]	--	0.69[a]	14	0.0041[a]	0.05[a]	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2014	7.96	2240[e,f,g,h]	--	1.15	0.667[a]	16	0.00413[a]	ND(0.098)	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	Encana Workforce Facility	187090W	WFF [40]	2011	9.37[e,f,g,h,i]	542[e,f,g]	ND(0.05)	--	--	35.2	4.93[a]	ND(0.098)	ND(0.1)	--	ND(1)	--	--
				2013	9.05[e,f,g,h,i]	540[e,f,g]	ND(0.1)	--	9.4[d,e,f,g]	39	5[j]	ND(0.24)	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
	Granite Wash Well 4461	36202W	BRD2 [30]	2011	8.8[e,f,g,i]	678[e,f,g]	0.399[e,g]	--	--	5.52	ND(0.026)	ND(0.0962)	ND(0.1)	--	ND(1)	--	--
				2013	8.03	670[e,f,g]	0.11	--	1.2	6.8	ND(0.005)	0.033[a]	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2014	8.42	696[e,f,g]	--	0.022[a]	1.38[a]	7.43	ND(0.005)	0.0435[a]	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	Holmes Federal #5-1W	196053W	HOL 5-1W [38]	2012	9.02[e,f,g,h,i]	800[e,f,g]	--	0.07[a]	8.9[d,e,f,g]	150[h]	0.11	ND(0.24)	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2013	8.55[e,f,g,i]	620[e,f,g]	0.081[a]	--	9.5[d,e,f,g]	65	0.59	ND(0.25)	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2014	8.86[e,f,g,i]	597[a,e,f,g]	--	ND(0.25)	9.79[a,d,e,f,g]	53.2[a]	ND(0.005)	0.0808[a]	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	South Desert #1	8531W	BF [24]	2013	8.68[e,f,g,i]	1600[e,f,g]	0.26	--	0.76	14	ND(0.005)	0.084[a]	0.011[a]	ND(1)	ND(1)	ND(1)	ND(2)
				2014	7.56	1600[e,f,g]	--	0.107	0.849[a]	16	0.0165	ND(0.098)	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	Tea Kettle Butte Well	96392W	TKB [1]	2011	9.2[e,f,g,h,i]	466	0.222	--	--	60.7	1.58	ND(0.0952)	ND(0.1)	--	ND(1)	--	--
				2013	9.22[e,f,g,h,i]	470	ND(0.1)	--	9.8[d,e,f,g]	55	1.8	ND(0.24)	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2014	8.79[e,f,g,i]	479	--	0.0217[a]	9.9[a,d,e,f,g]	60.4	1.66	ND(0.1)	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	Buckhorn #308	9361P	BHW2 [20]	2011	10.05[e,f,g,h,i]	2490[e,f,g,h]	17.9[e,g,h]	--	--	145[h]	0.054	0.232	ND(0.1)	--	ND(1)	--	--
				2012	9.55[e,f,g,h,i]	2400[e,f,g,h]	--	0.082[a]	5.3[d,e,f,g]	61	0.03	ND(0.24)	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
	Burma Road Well #3	99087W	BRD1 [34]	2011	8.51[e,f,g,i]	2930[e,f,g,h]	3.65[e,g]	--	--	86.8	ND(0.026)	ND(0.0952)	ND(0.1)	--	ND(1)	--	--
				2012	--	2800[e,f,g,h]	--	0.043[a]	2.3[e]	82	0.003	ND(0.24)	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2014	8.20	2840[e,f,g,h]	--	ND(0.25)	2.03[a,e]	83.8	0.00385[a]	ND(0.0962)	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	--	--	Err1/NP2 [6]	2011	9.45[e,f,g,h,i]	516[e,f,g]	ND(0.05)	--	--	93.8	11.1[j]	ND(0.0962)	ND(0.1)	--	ND(1)	--	--
				2012	9.82[e,f,g,h,i]	510[e,f,g]	--	ND(0.1)	11[d,e,f,g]	97	2.4[a]	ND(0.24)	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2014	9.32[e,f,g,h,i]	515[e,f,g]	--	ND(0.25)	11[a,d,e,f,g]	95.9	7.85[j]	0.0373[a]	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	Bloom Well	9347P	P9347 [15]	2011	8.05	4010[e,f,g,h]	4.38[e,g]	--	--	31.1	ND(0.026)	ND(0.0952)	ND(0.1)	--	ND(1)	--	--
				2012	7.61	3900[e,f,g,h]	--	0.04[a]	1.4	29	0.0017	ND(0.24)	0.013[a]	ND(1)	ND(1)	ND(1)	ND(2)
				2014	8.06	3740[e,f,g,h]	--	ND(0.25)	1.39[a]	27.1	0.00965	0.0549[a]	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)

Table C-1. Water Quality Results from Water Wells in and around the NPL Project Area

Field	Well Name (SEO Facility)	SEO Permit No.	Trihydro Reference Name [Well/Map Reference No.][c]	Data Year	pH (Standard Units)	Total Dissolved Solids (mg/L)	Iron - Total (mg/L)	Iron - Dissolved (mg/L)	Fluoride (mg/L)	Chloride (mg/L)	Methane (mg/L)	DRO (mg/L)	GRO (mg/L)	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	Xylenes (µg/L)
	Davis Old Road Unit #1 Water	54621W	STA [3]	2011	8.56[e,f,g,i]	1040[e,f,g]	0.134	--	--	362[e,f,g,h]	0.17	ND(0.0962)	ND(0.1)	--	ND(1)	--	--
				2012	8.81[e,f,g,i]	990[e,f,g]	--	ND(0.1)	14[d,e,f,g]	390[e,f,g,h]	0.2	ND(0.24)	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2014	8.52[e,f,g,i]	857[e,f,g]	--	0.111	12.6[a,d,e,f,g]	294[e,f,g,h]	1.62	0.063[a]	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	Sugar Loaf Well #390	9620P	Rees1 [27]	2011	7.97	2610[e,f,g,h]	0.289	--	--	21.2	ND(0.026)	ND(0.0943)	ND(0.1)	--	ND(1)	--	--
	Sugar Loaf #389	9619P	Rees2 [23]	2011	8.99[e,f,g,i]	1580[e,f,g]	0.72[e,g]	--	--	19.8	ND(0.026)	ND(0.111)	ND(0.1)	--	ND(1)	--	--
	14cbd02	--	NP4 [7]	2014	9.05[e,f,g,h,i]	809[e,f,g]	--	ND(0.25)	16.3[a,d,e,f,g]	135[h]	1.2	0.0918[a]	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	Boundary #4645	51229W	-- [11]	2014	9.75[e,f,g,h,i]	373	--	0.0105[a]	6.72[a,d,e,f,g]	46.1	0.259	ND(0.0962)	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	Midland Well 2011-2	195392W	-- [58]	2014	8.72[e,f,g,i]	1080[e,f,g]	--	ND(0.025)	17.8[a,d,e,f,g]	373[e,f,g,h]	8.5[j]	0.706	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	Radio Tower 1-8 WW	180214W	-- [5]	2014	9.39[e,f,g,h,i]	641[e,f,g]	--	ND(0.25)	3.28[a,e]	8.1	0.00374[a]	0.0674[a]	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	Davis Luman Road Water	41168W	-- [2]	2014	9.20[e,f,g,h,i]	638[e,f,g]	--	ND(0.25)	9.69[a,d,e,f,g]	111[a,h]	2.98	0.0492[a]	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	Buckhorn Well #313	9360P	-- [22]	2014	7.04	4330[e,f,g,h]	--	0.0311	1.36[a]	37.1	0.00333[a]	0.0371[a]	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
Jonah	Cabrito 13-19W	193708W	--	2013	10.0[b,e,f,g,h,i]	308	ND(0.03)	ND(0.03)	--	44	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Corona 2-14	183409W	-- [61]	2013	10.5[e,f,g,h,i]	453	--	ND(0.050)	--	46.1	--	ND(0.50)	ND(500)	11.8[d,f]	2.6	ND(1.0)	ND(3.0)
	Corona 7-19	200462W	--	2013	10.3[e,f,g,h,i]	320	--	3.8	--	36.9	--	ND(0.50)	ND(500)	ND(1.0)	27.1	ND(1.0)	ND(3.0)
	Corona 7-19 Dup	200462W	--	2013	10.3[e,f,g,h,i]	315	--	0.137	--	36.9	--	ND(0.50)	ND(500)	ND(1.0)	26.7	ND(1.0)	ND(3.0)
	Jonah Fed (SHB) 32-34	195782W	--	2013	9.6[b,e,f,g,h,i]	656[e,f,g]	0.21	ND(0.03)	--	19	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Jonah Fed 2-5W	195992W	-- [63]	2013	8.6[b,e,f,g,i]	1690[e,f,g]	0.39[e,g]	0.13	--	32	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Jonah Fed 2-7W	193709W	--	2013	9.2[b,e,f,g,h,i]	1010[e,f,g]	0.8[e,g]	ND(0.03)	--	43	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Jonah Field Office	--	--	2013	9.29[e,f,g,h,i]	286	--	ND(0.050)	--	41.8	--	ND(0.50)	ND(500)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Stud Horse Butte 10-28W	171643W	--	2013	9.2[b,e,f,g,h,i]	591[e,f,g]	0.06	ND(0.03)	--	121[h]	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Stud Horse Butte 10-32W	195826W	--	2013	9.0[b,e,f,g,h,i]	1590[e,f,g]	0.79[e,g]	0.06	--	16	--	ND(0.30)	ND(0.020)	ND(1.0)	0.44[a]	ND(1.0)	0.85[a]
	Stud Horse Butte 10-34W	195779W	--	2013	9.6[b,e,f,g,h,i]	610[e,f,g]	0.07	ND(0.03)	--	25	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Stud Horse Butte 10-34W (Duplicate)	195779W	--	2013	9.6[b,e,f,g,h,i]	633[e,f,g]	0.12	ND(0.03)	--	25	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Stud Horse Butte 11-20W	195829W	-- [64]	2013	9.4[b,e,f,g,h,i]	565[e,f,g]	0.05	ND(0.03)	--	56	--	ND(0.30)	0.326	4.8	38	3.2	35
	Stud Horse Butte 11-20W (Duplicate)	195829W	--	2013	--	--	--	--	--	--	--	ND(0.30)	ND(0.020)	2.1	7.5	0.30[a]	3.1
	Stud Horse Butte 11-26W	180553W	--	2013	9.5[b,e,f,g,h,i]	466	0.04	ND(0.03)	--	73	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Stud Horse Butte 11-29W	195997W	--	2013	8.9[b,e,f,g,i]	1870[e,f,g]	0.44[e,g]	0.04	--	20	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Stud Horse Butte 122-10	192164W	--	2013	9.8[b,e,f,g,h,i]	514[e,f,g]	0.85[e,g]	0.11	--	13	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Stud Horse Butte 13-32W	193916W	--	2013	8.5[b]	2460[e,f,g,h]	0.52[e,g]	0.03	--	21	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Stud Horse Butte 15-16	198795W	--	2013	9.91[e,f,g,h,i]	439	--	ND(0.050)	--	76.6	--	ND(0.50)	ND(500)	ND(1.0)	ND(1.0)	ND(1.0)	ND(3.0)
	Stud Horse Butte 16-20	198796W	-- [62]	2013	9.98[e,f,g,h,i]	525[e,f,g]	--	0.162	--	10.3	--	ND(0.50)	ND(500)	1.0	4.6	ND(1.0)	5.7
	Stud Horse Butte 23-16	199923W	--	2013	10.1[e,f,g,h,i]	299	--	ND(0.050)	--	38.1	--	ND(0.50)	ND5(500)	ND(1.0)	ND(1.0)	ND(1.0)	ND(3.0)
	Stud Horse Butte 4-36W	196598W	--	2013	9.7[b,e,f,g,h,i]	360	0.12	0.03	--	68	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Stud Horse Butte 7-33W	195827W	-- [65]	2013	9.4[b,e,f,g,h,i]	536[e,f,g]	0.04	ND(0.03)	--	91	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Stud Horse Butte 8-34W	195828W	--	2013	9.8[b,e,f,g,h,i]	493	0.07	ND(0.03)	--	9	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)

Table C-1. Water Quality Results from Water Wells in and around the NPL Project Area

Field	Well Name (SEO Facility)	SEO Permit No.	Trihydro Reference Name [Well/Map Reference No.][c]	Data Year	pH (Standard Units)	Total Dissolved Solids (mg/L)	Iron - Total (mg/L)	Iron - Dissolved (mg/L)	Fluoride (mg/L)	Chloride (mg/L)	Methane (mg/L)	DRO (mg/L)	GRO (mg/L)	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	Xylenes (µg/L)
	Stud Horse Butte 9-32W	168426W	--	2013	8.4[b]	1910[e,f,g]	25.7[e,f,g,h]	0.31	--	32	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Stud Horse Butte 9-32W (Duplicate)	168426W	--	2013	8.4[b]	1880[e,f,g]	28.9[e,f,h]	ND(0.03)	--	32	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Yellow Point 10-11W	196048W	--	2013	8.6[b,e,f,g,i]	4370[e,f,g,h]	13.2[e,g,h]	0.06	--	42	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
	Yellow Point 1-13W	184873W	--	2013	9.3[b,e,f,g,h,i]	1100[e,f,g]	0.21	0.05	--	34	--	ND(0.30)	ND(0.020)	ND(1.0)	ND(1.0)	ND(1.0)	ND(1.0)
Other	Desert Well #2	10502P	DW2 [48]	2011	9.25[e,f,g,h,i]	916[e,f,g]	0.614[e,g]	--	--	70.1	ND(0.026)	ND(0.0952)	ND(0.1)	--	ND(1)	--	--
				2013	8.44	1000[e,f,g]	0.21	--	6.3[d,e,f,g]	62	0.00099[a]	ND(0.24)	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2014	8.57[e,f,g,i]	1050[e,f,g]	--	0.457	7.1[a,d,e,f,g]	67.4	ND(0.005)	0.0612[a]	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	North Sublette Meadow Spring	--	NSMS/NP3 [45]	2011	8.84[e,f,g,i]	1480[e,f,g]	0.407[e,g]	--	--	6.01	ND(0.026)	0.104	ND(0.1)	--	ND(1)	--	--
				2013	8.91[e,f,g,i]	1400[e,f,g]	0.2	--	2.9[e]	22	0.014	0.042[a]	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2014	--	1390[e,f,g]	--	ND(0.25)	3.1[a,e]	24.3	0.00536	0.0481[a]	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	Sagebrush 14-20WW	163911W	SBW [47]	2011	9.05[e,f,g,h,i]	600[e,f,g]	0.0588	--	--	37.3	0.0668	ND(0.0962)	ND(0.1)	--	ND(1)	--	--
				2013	9.37[e,f,g,h,i]	580[e,f,g]	0.03[a]	--	8.8[d,e,f,g]	35	0.049	ND(0.26)	ND(0.025)	ND(1)	ND(1)	ND(1)	ND(2)
				2014	8.55[e,f,g,i]	588[e,f,g]	--	0.0168[a]	8.74[a,d,e,f,g]	34.9	0.0307	ND(0.098)	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	Fear Well #1	6874W	FEAR1 [49]	2011	8.1	1420[e,f,g]	1.14[e,g]	--	--	19	ND(0.026)	ND(0.0943)	ND(0.1)	--	ND(1)	--	--
				2013	8.55[e,f,g,i]	1500[e,f,g]	0.36[e,g]	--	0.8	17	0.00091[a]	0.038[a]	0.028	ND(1)	7.4	ND(1)	ND(2)
				2014	8.08	1540[e,f,g]	--	0.0296	0.836[a]	19.3	0.00905	0.0962	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)
	North Alkali #1	8432P	NA1 [54]	2011	8.01	1130[e,f,g]	2.18[e,g]	--	--	15	ND(0.026)	ND(0.0943)	ND(0.1)	--	ND(1)	--	--
				2013	7.7	1200[a,e,f,g]	6[e,g,h]	--	1.3	16	ND(0.005)	ND(0.24)	0.017[a]	ND(1)	ND(1)	ND(1)	ND(2)
	Emigrant Trail Well 4518	51216W	ETW [43]	2011	9.24[e,f,g,h,i]	1210[e,f,g]	0.572[e,g]	--	--	245[h]	23.7[j]	1.26[a,f]	ND(0.1)	--	22.8	--	--
				2012	9.16[e,f,g,h,i]	1200[e,f,g]	--	0.024[a]	21[d,e,f,g]	290[e,f,g,h]	11[j]	0.23[a]	0.01[a]	ND(4)	ND(4)	ND(4)	ND(8)
	Oasis Well	10507P	Oasis [50]	2011	7.78	5820[e,f,g,h,i]	9.31[e,g,h]	--	--	104[h]	ND(0.026)	ND(0.0943)	ND(0.1)	--	ND(1)	--	--
				2012	8.59[e,f,g,i]	6300[e,f,g,h,i]	--	0.041[a]	1.3[a]	110[h]	0.0069[a]	ND(0.24)	0.024[a]	ND(1)	ND(1)	ND(1)	ND(2)
	--	--	PA1 [46]	2011	9.45[e,f,g,h,i]	562[e,f,g]	ND(0.05)	--	--	37.2[a]	2.47	ND(0.0952)	ND(0.1)	--	ND(1)	--	--
				2012	9.86[e,f,g,h,i]	560[e,f,g]	--	ND(0.1)	8.2[d,e,f,g]	39	0.81[a]	ND(0.24)	0.012[a]	ND(1)	ND(1)	ND(1)	ND(2)
	McGinnis #2	--	McGinnis 2 [56]	2011	9.45[e,f,g,h,i]	670[e,f,g]	ND(0.05)	--	--	15.2[a]	ND(0.026)	ND(0.0952)	ND(0.1)	--	ND(1)	--	--
	Ross Ridge Well #4310	--	BRD3 [57]	2011	7.34	2530[e,f,g,h]	0.971[e,g]	--	--	80.2	ND(0.026)	ND(0.0971)	ND(0.1)	--	ND(1)	--	--
	Desert Well #1	10501P	DW1 [44]	2011	8.25	3340[e,f,g,h]	0.11	--	--	69.9	ND(0.026)	ND(0.098)	ND(0.1)	--	ND(1)	--	--
	Reservoir #4638	51222W	FEWE [52]	2011	8.77[e,f,g,i]	453	0.138	--	--	5.68	ND(0.026)	ND(0.0962)	ND(0.1)	--	ND(1)	--	--
	--	--	GFW [53]	2011	8.89[e,f,g,i]	1300[e,f,g]	0.6[e,g]	--	--	18.1	ND(0.026)	ND(0.0952)	ND(0.1)	--	ND(1)	--	--
	Green River #2	6877W	GRW2 [51]	2011	9.08[e,f,g,h,i]	1380[e,f,g]	0.452[e,g]	--	--	33.9	ND(0.026)	ND(0.0943)	ND(0.1)	--	ND(1)	--	--
	--	--	McGinnis 1 [55]	2011	9.27[e,f,g,h,i]	664[e,f,g]	ND(0.05)	--	--	19.4[a]	ND(0.026)	ND(0.0943)	ND(0.1)	--	ND(1)	--	--
	JIO Boundary Well	191117W	-- [60]	2014	9.17[e,f,g,h,i]	570[e,f,g]	--	ND(0.25)	3.35[a,e]	11.4	0.0209	0.091	ND(0.1)	ND(0.5)	ND(0.5)	ND(0.5)	ND(1.5)

Table C-1. Water Quality Results from Water Wells in and around the NPL Project Area

Field	Well Name (SEO Facility)	SEO Permit No.	Trihydro Reference Name [Well/Map Reference No.][c]	Data Year	pH (Standard Units)	Total Dissolved Solids (mg/L)	Iron - Total (mg/L)	Iron - Dissolved (mg/L)	Fluoride (mg/L)	Chloride (mg/L)	Methane (mg/L)	DRO (mg/L)	GRO (mg/L)	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	Xylenes (µg/L)

Sources: AECOM 2014; AMEC 2014; Trihydro 2011, 2012, 2014a, 2014b; Wyoming SEO 2014

[a]Estimated quantified (i.e., detected) value
[b]pH measured in the laboratory
[c]Map reference number refers to the numbered wells presented in Figure K-7 and Figure K-8. Some wells are not depicted on these maps and therefore will not have a reference number.

"—" = not available; no measurement taken
ND(0.0) = Non-detect(reporting limit)
mg/L milligrams per liter
µg/L micrograms per liter

Note: Wyoming SEO records are updated regularly, and permitting information included at the time of this report is based on current information.

Note: Water quality standards or limits are provided in Table C-2 below. Observations that exceed any recommended standards or limits are highlighted orange and noted with the following:

[d]Exceeds the EPA Primary Drinking Water Standard
[e]Exceeds the EPA Secondary Drinking Water Standard
[f]Exceeds the Wyoming Groundwater Cleanup Level
[g]Exceeds the WDEQ Class I – Domestic Use Suitability
[h]Exceeds the WDEQ Class II – Agriculture Use Suitability
[i]Exceeds the WDEQ Class III – Livestock Use Suitability
[j]Exceeds another established standard or recommended safety level

Table C-2. Water Quality Regulatory Standards and Limits

Parameter/Constituent	EPA Primary Drinking Water Standard	EPA Secondary Drinking Water Standard	Wyoming Groundwater Cleanup Level	WDEQ Underground Water Class Use Suitability			Other
				Class I - Domestic	*Class II - Agriculture*	*Class III - Livestock*	
pH	--	6.5 - 8.5	6.5 - 8.5	6.5 - 8.5	4.5 - 9.0	6.5 - 8.5	--
Total Dissolved Solids (TDS)	--	500 mg/L	500 mg/L	500 mg/L	2,000 mg/L	5,000 mg/L	--
Iron - Total	--	0.3 mg/L	25.5 mg/L	0.3 mg/L	5.0 mg/L	--	--
Iron - Dissolved	--	--	--	--	--	--	--
Fluoride	4.0 mg/L	2.0 mg/L	4.0 mg/L	4.0 mg/L	--	--	--
Chloride	--	250 mg/L	250 mg/L	250 mg/L	100 mg/L	2,000 mg/L	--
Methane	--	--	--	--	--	--	5.0 mg/L warrants isotope analysis; >10 mg/L but <28 mg/L warrants investigation and > 28 mg/L warrants immediate action due to risk of an explosion
Diesel Range Organics (DRO)	--	--	1.1 mg/L (if benzene is present); 10 mg/L (if benzene is absent)	--	--	--	--
Gasoline Range Organics (GRO)	--	--	7.3 mg/L	--	--	--	--
Benzene	5 µg/L	--	5 µg/L	--	--	--	--
Toluene	1,000 µg/L	--	1,000 µg/L	--	--	--	--
Ethylbenzene	700 µg/L	--	700 µg/L	--	--	--	--
Xylenes - Total	10,000 µg/L	--	10,000 µg/L	--	--	--	--

Sources: Eltschlager et al. 2001; EPA 2009; WDEQ 2013, 2015.

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