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NUMERICAL GROUNDWATER MODELING REPORT
INTERIM PLAN

Pinedale Anticline Project Area ROD
Sublette County, Wyoming

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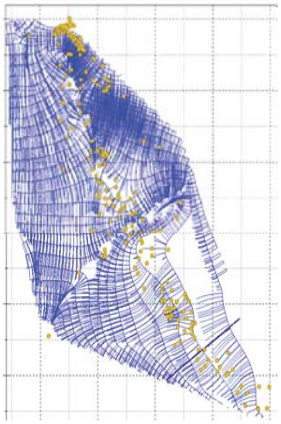

Wyoming Department of Environmental Quality

QEP Energy

Ultra Resources, Inc.

O C T O B E R 2 0 1 3

NUMERICAL GROUNDWATER MODELING REPORT

PINEDALE ANTICLINE OIL AND GAS EXPLORATION AND DEVELOPMENT PROJECT

Sublette County, Wyoming

Prepared for:

U.S. Department of Interior, Bureau of Land Management, Pinedale Field Office Wyoming Department of Environmental Quality, Water Quality Division
U.S. Environmental Protection Agency, Region 8
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EXECUTIVE SUMMARY

This report documents the conceptualization and design of a numerical groundwater flow model for the groundwater system in the Pinedale Anticline Oil and Gas Exploration and Production Area (also known as the Pinedale Anticline Project Area, or PAPA). AMEC Environment & Infrastructure, Inc. (AMEC; formerly Geomatrix Consultants, Inc. [Geomatrix], and AMEC Geomatrix, Inc.), was retained to complete the numerical groundwater model on behalf of Ultra Resources, Inc. (Ultra), SWEPI LP (Shell), and QEP Energy (QEP) (known collectively as Operators). NewFields Companies, LLC has assisted AMEC in this modeling work since September 2012. This report is the second of four technical reports pursuant to the *Interim Groundwater/Aquifer Pollution Prevention, Mitigation and Monitoring Plan* (Interim Plan). The Interim Plan was designed to fulfill certain requirements specified by the U.S. Department of Interior, Bureau of Land Management (BLM), in the Record of Decision (ROD) for the *Final Supplemental Environmental Impact Statement (SEIS) for the Pinedale Anticline Oil and Gas Exploration and Development Project, Sublette County, Wyoming*. Based on a detailed Plan of Study for a hydrogeologic data gaps investigation issued in May 2009, AMEC completed extensive field studies between 2009 and 2011. The Hydrogeologic Data Gaps Investigation, the first technical report, discusses results from completed field investigations and includes an updated hydrogeologic conceptualization of the PAPA's shallow groundwater system. The Hydrogeological Data Gaps Investigation forms the basis for the numerical groundwater flow and transport models discussed in this report.

The work described in this report was developed to achieve the following objectives:

- Construct a numerical model that is capable of simulating regional groundwater flow under steady-state conditions.
- Identify areas and specific receptors in the PAPA that are potentially vulnerable to contamination from natural gas activities should a significant release occur.
- Assess fate and transport of petroleum hydrocarbons and chloride that could potentially result from hypothetical releases.
- Predict the maximum lateral and vertical extent of impacts and maximum concentrations of contaminants in groundwater resulting from hypothetical releases.

CONCEPTUAL MODEL

Development of a conceptual model is the first step in the numerical modeling process. The majority of the PAPA is underlain by the Tertiary-age Wasatch Formation, consisting primarily of fluvially deposited sandstones representing channel deposits, and shale/siltstone representing overbank deposits. Sandstone and shale/siltstone are interbedded, and laterally discontinuous. Other geologic units in the PAPA include alluvial sand and gravel deposits in stream valleys with depths typically less than 100 feet, and a veneer of terrace gravel over the highland area known as the Mesa. The majority of groundwater flow occurs within Wasatch Formation sandstone lenses, alluvial deposits along streams, and glacial deposits draining the Wind River Mountains. Groundwater generally flows west and south from the mountains and foothills toward the Green River below the mouth of the New Fork River and into the center of the Green River Basin. Groundwater preferentially flows through higher permeability sandstone units within the Wasatch Formation. The majority of groundwater within the Wasatch and alluvial

groundwater systems discharges to the lower New Fork River in the center of the PAPA. South of the river, groundwater flows to the west- southwest toward the center of the Green River Basin. The alluvial groundwater system is connected to the Wasatch system, receiving and transmitting water down valley and into the New Fork River in the central PAPA. Based on contrasts in hydraulic conductivity between fine-grained units and sandstone, the discontinuous nature of individual sandstone beds, and hydraulic potentials that commonly rise above the top of the saturated zone, the Wasatch hydrostratigraphic unit in the PAPA is likely a semi-confined aquifer.

A groundwater balance was developed for the model domain based on field data and literature information. Mountain front recharge is the greatest source of groundwater. Other sources of recharge include natural recharge from precipitation and runoff, infiltration of irrigation water, and leakage from irrigation ditches. The majority of groundwater in the area discharges to the New Fork River. Groundwater also discharges from the system by evapotranspiration from wetlands and riparian phreatophytes and by pumping from stock, domestic, and industrial wells.

MODEL DESIGN

The model domain is 547 square miles inclusive of the PAPA boundary. The margins of the model domain are based on hydraulic boundaries. The model is bounded to the west by the Green River and to the south by a hydraulic divide and an underflow boundary defined by a potentiometric contour. The model is bounded to the east by the Big Sandy River and to the northeast by an underflow boundary defined by a potentiometric contour. The model contains 205 rows, 171 columns, and 69 layers with variable grid spacing. Model layers were defined by lithologic modeling incorporating data from 243 wells and represent alternating units of shale/siltstone with sandstone. The computer code MODFLOW-SURFACT was selected for the project because it has all the required capabilities for the study based on modeling objectives, the size and complexity of the project area, and hydrologic features expected to affect groundwater flow within the study area. Hydrologic boundary conditions in the model domain include general head boundary cells representing underflow; cells representing streams, rivers, and ditches simulated with the River Package; areal recharge simulated with the Recharge Package; evapotranspiration simulated with the Evapotranspiration Package; and pumping wells simulated with the Fracture Well Package.

MODEL CALIBRATION

The model is calibrated to steady-state conditions represented by average annual groundwater elevation and flux targets. A set of 97 calibration head target values were developed based on groundwater elevations measured in 2009, 2010, and 2011. Flux targets are based on estimates developed for the groundwater balance. Model calibration was completed using an iterative approach that included both manual and automated techniques (including parameter estimation using the PEST program) resulting in several hundred model iterations. Horizontal and vertical hydraulic conductivity and stream channel and ditch bottom conductance values were adjusted during calibration to minimize residuals. Qualitative and quantitative evaluation of results indicate the model is well calibrated.

A sensitivity analysis was performed on the calibrated steady-state model by systematically adjusting parameters within a reasonable range to see the effect on calibration statistics. The calibration is least sensitive to evapotranspiration rate and extinction depth and most sensitive to horizontal hydraulic conductivity and total recharge.

TRANSPORT SIMULATIONS

Advective and solute transport modeling was completed to meet the project objectives. Advective transport was simulated using particle tracking techniques and MODPATH software. Particle tracking was used to identify areas and specific receptors in the PAPA that are potentially susceptible to contamination from natural gas activities should a significant release occur. Potential sources of groundwater contamination associated with natural gas operations and potential receptors of concern in and around the PAPA were identified. Potential sources include shut-in pre-1984 natural gas wells, liquid-gathering facilities, natural gas pads, pipelines, roads, and saltwater disposal facilities. Forward and reverse particle tracking methods were used to evaluate flow paths and advective travel times from potential sources to potential receptors.

Solute transport modeling was performed in the area determined from advective modeling to be most susceptible to groundwater quality impacts to assess fate and transport of certain petroleum hydrocarbon compounds and chloride that could potentially result from five hypothetical release scenarios. Source terms for each scenario were developed based on conservative assumptions. Modeling included predicting the maximum lateral and vertical extent of impacts and maximum concentrations of contaminants in groundwater resulting from hypothetical releases. This analysis does not represent actual contamination in the aquifer, but instead was used to evaluate flow paths and travel times from hypothetical sources and receptors and to demonstrate model capabilities.

Solute transport modeling addressed the following five hypothetical release scenarios:

1. A truck spill of condensate on Paradise Road;
2. A pipeline leak of produced water north of the New Fork River and south of the Mesa;
3. A spill of condensate due to failure of a storage tank at a liquid-gathering facility;
4. A frac tank spill on a natural gas pad; and
5. A leak from shut-in pre-1984 natural gas well Pinedale 3.

Conservative assumptions were used for all particle tracking and solute transport scenarios discussed in this report and assume no secondary containment, cleanup, or remediation of the hypothetical releases.

FINDINGS

Fate and transport modeling resulted in the following key findings:

- Natural gas activities in the PAPA will not affect groundwater in or around the town of Pinedale.
- In general, particles in groundwater do not travel more than 1.5 miles in 110 years in areas within the PAPA outside of the river corridors. Based on solute transport modeling, only conservative solutes (those that do not adsorb to aquifer material, react chemically, or undergo biological degradation), such as chloride, would travel this distance. Traveling at the average linear groundwater velocity in the Wasatch Formation, it would take a particle 9 years to travel the typical width of an individual natural gas well pad (650 feet).
- The area most susceptible to groundwater quality impacts related to a significant release to groundwater from natural gas activities is the New Fork River valley between Boulder Creek and the downstream PAPA boundary. This conclusion is based on conservative assumptions and

the combination of this area's proximity downgradient of potential source areas, relatively rapid groundwater travel times, and existing receptors including the New Fork River and groundwater users. Results suggest future groundwater monitoring should focus on this area; however, the identification of this area and potential receptors does not imply any probability of future impacts to water resources in this area.

- Results of five hypothetical release scenarios simulated within the area most susceptible to groundwater quality impacts described above indicate that predicted concentrations of benzene and toluene in groundwater do not exceed U.S. EPA maximum contaminant levels for drinking water at distances greater than 150 feet away from simulated sources. Since most of the potential receptors in this area are greater than 150 feet from oil and gas activities, and even if a major release to groundwater were to occur within this area, impacts related to petroleum hydrocarbons would be unlikely to reach most of these receptors.
- An individual release of petroleum hydrocarbons from natural gas exploration and production activities is unlikely to impact large portions of the Wasatch or alluvial aquifers due to relatively low groundwater velocities, retardation, and biodegradation.
- The numerical model is appropriate for predicting flow and transport at an intermediate and regional scale. The model results are helpful in identifying regions within the aquifer system (and in rivers/streams where groundwater is connected to surface water) that are most susceptible to groundwater quality impacts, and identifying appropriate locations for long-term water quality monitoring.

LIMITATIONS

Groundwater elevation targets are concentrated in and around the axis of the Pinedale Anticline, and scarcity of data outside this area leads to increased model uncertainty.

The transport model described above has not been calibrated to existing conditions because information regarding source terms is not available. For this reason, the predictive capabilities of the transport model have not been evaluated. Conservative assumptions were used for solute transport model inputs.

Model cells are larger than the areas within which the hypothetical release was assumed to occur. Because of the model cell size, the model cannot simulate small-scale (<300 feet) heterogeneity in the unsaturated and saturated zones. As a result, the model is not capable of accurately simulating concentrations at a small scale (<300 feet); however, the model is appropriate for simulating large-scale (>300 feet) movement of potential releases and travel times from potential sources to potential receptors.

Limited information is available regarding the location of fractures and faults in the Wasatch Formation, and no information is available regarding hydraulic properties of fractures and faults. Fractures and faults can act as both conduits and barriers to flow and contaminant transport. For this reason, the model assumes that groundwater flows through a porous medium and that no preferential flow occurs through fractures in the Wasatch Formation. In reality, some preferential flow paths associated with geologic structure and secondary porosity likely exist; permeable fractures could affect groundwater flow directions and transport velocities.

ACRONYMS AND ABBREVIATIONS

3D	three-dimensional
µg/L	micrograms/liter
AMEC	AMEC Environment & Infrastructure, Inc./AMEC Geomatrix, Inc.
amsl	above mean sea level
BDE	U.S. Department of Interior, Bureau of Land Management; Wyoming Department of Environmental Quality – Water Quality Division; and U.S. Environmental Protection Agency
bgs	below ground surface
BLM	U.S. Department of Interior, Bureau of Land Management
DEM	digital elevation model
DEQ	Wyoming Department of Environmental Quality
DTW	depth to water
EPA	U.S. Environmental Protection Agency
ET	evapotranspiration
$feet^3$	cubic feet
Geomatrix	Geomatrix Consultants, Inc.
GHB	General Head Boundary
GW	groundwater
HSU	hydrostratigraphic unit
LEL	lower explosive limit
LLPHC	low-level petroleum hydrocarbon compound
mg/L	milligrams/liter
MVS	Mining Visualization System
Operators	Ultra Resources, Inc., SWEPI LP, and QEP Energy
PAPA	Pinedale Anticline Oil and Gas Exploration and Production Area
PEST	Parameter Estimation
PET	potential evapotranspiration
POS	plan of study
PQL	practical quantitation limit
QEP	QEP Energy
ROD	Record of Decision
SAR	sodium adsorption ratio
SCCD	Sublette County Conservation District
SEIS	Final Supplemental Environmental Impact Statement for the Pinedale Anticline Oil and Gas Exploration and Development Project, Sublette County, Wyoming
Shell	SWEPI LP
TDS	total dissolved solids
Ultra	Ultra Resources, Inc.
USGS	U.S. Geological Survey
WSEO	Wyoming State Engineers Office
WSGS	Wyoming State Geologic Society

1.0 INTRODUCTION

AMEC Environment & Infrastructure, Inc. (AMEC; formerly Geomatrix Consultants, Inc. [Geomatrix], and AMEC Geomatrix, Inc.), was retained by Ultra Resources, Inc. (Ultra), SWEPI LP (Shell), and QEP Energy (QEP) (referred to collectively as the Operators) to develop a numerical model of the groundwater system in the Pinedale Anticline Oil and Gas Exploration and Production Area (PAPA), Sublette County, Wyoming. NewFields Companies, LLC has assisted AMEC in this modeling work since September 2012. The PAPA covers approximately 309 square miles of federal, state, and private land, with an approximate maximum width of 14 miles and length of about 30 miles. The U.S. Department of Interior, Bureau of Land Management (BLM) manages 80 percent of the land within the PAPA.

In 2008, the BLM issued a Record of Decision (ROD) related to the *Final Supplemental Environmental Impact Statement for the Pinedale Anticline Oil and Gas Exploration and Development Project, Sublette County, Wyoming* (SEIS) (BLM, 2008b). The ROD documents the Department of Interior's decision for the SEIS and in part required characterization of the groundwater system and development of an interim groundwater protection plan. A consortium of federal and state agencies in cooperation with the Operators prepared an *Interim Groundwater/Aquifer Pollution Prevention, Mitigation and Monitoring Plan* (Interim Plan; Geomatrix, 2008a) that was designed to fulfill specific requirements of the ROD (BLM, 2008a). The consortium consists of representatives and technical specialists with the BLM, Wyoming Department of Environmental Quality (DEQ) – Water Quality Division, and the U.S. Environmental Protection Agency (EPA), as well as representatives of the Operators. For purpose of this report, these federal and state agencies are collectively referred to as "BDE." The Interim Plan defined a general strategy to characterize the hydrogeology of the PAPA, evaluate Operator practices with respect to potential impacts to groundwater resources, and identify monitoring and mitigation strategies to address known hydrocarbon occurrences in groundwater.

This report documents the development of a groundwater flow and transport model that was designed to enhance understanding of hydrogeologic characteristics of the groundwater system and aid in designing groundwater monitoring strategies in the PAPA. The cumulative result of data collected as part of the Interim Plan and subsequent data analysis, including the groundwater flow model, will be the *Final Groundwater/Aquifer Pollution Prevention, Mitigation, and Monitoring Plan* designed to help protect groundwater resources in the PAPA. AMEC is providing technical support on behalf of the Operators related to the requirements of the Interim Plan.

The numerical groundwater model is intended to serve as a technical tool to support decision-making regarding protection of groundwater resources in the PAPA. The numerical groundwater model will support development of strategies to prevent groundwater pollution and design of a groundwater monitoring program to assess groundwater conditions in the PAPA.

The work described in this report was developed to achieve the following objectives:

- Construct a numerical model that is capable of simulating regional groundwater flow under steady-state conditions.
- Identify areas and specific receptors in the PAPA that are potentially susceptible to groundwater quality impacts from natural gas activities should a significant release occur.

- Assess fate and transport of petroleum hydrocarbons and chloride that could potentially result from hypothetical releases.
- Predict the maximum lateral and vertical extent of impacts and maximum concentrations of contaminants in groundwater resulting from hypothetical releases.

This report documents development of the groundwater flow model, including presentation of the hydrogeologic conceptual model that formed the basis of the numerical model, an overview of steps used to design and calibrate the numerical model, and hypothetical advective and solute transport modeling results.

1.1 Project Background

To fulfill water resources inventory and monitoring requirements of BLM's initial ROD (BLM, 2000), the Operators contracted the Sublette County Conservation District (SCCD) to complete an inventory of wells, develop a surface water and groundwater monitoring program, and collect and manage the resulting data. The SCCD began collecting surface water and groundwater data in the PAPA in 2000-2001. The SCCD maintains a water quality database and reports their findings to the BLM annually. SCCD's database contains water quality and available depth-to-water data for domestic, stock, and industrial water supply wells located within 1 mile of existing or proposed oil and gas development or exploration activities.

In 2007, the Operators retained Geomatrix to compile and analyze existing groundwater data in the PAPA, and develop a hydrogeologic conceptual model (Geomatrix, 2008b). Based on hydrogeologic analysis using existing information, Geomatrix (2008b) identified several data gaps. BLM's ROD for the SEIS (BLM, 2008a) required characterization of the groundwater system. As dictated by the Interim Plan (Geomatrix, 2008a), Geomatrix developed a plan of study (POS) to fill identified hydrogeologic data gaps and improve the understanding of the groundwater system in the PAPA. The BDE and Operators approved the POS in May 2009 (AMEC, 2009a). The POS outlined multiple objectives that included:

- Establish contemporaneous water elevation data.
- Determine gain-loss characteristics of the New Fork River.
- Evaluate surface water/groundwater interconnection.
- Determine hydraulic properties for each hydrostratigraphic unit.
- Investigate hydraulic connection between each hydrostratigraphic unit.
- Revise the hydrogeologic conceptual model to address new data.

Results from data collection and analysis (AMEC, 2012) and execution of a sampling and analysis plan for evaluating low-level petroleum hydrocarbon compounds (AMEC, 2010) form the basis for developing the conceptual groundwater flow and transport models, which were in turn used to construct the numerical models described in this report. The chart below summarizes tasks completed by AMEC to date, related to the different studies.

	Date	Event	Data Types
2009	April 2009	Survey credible wells and SW stations	Location, elevation, LEL, DTW
	July 2009	Spring inventory (Mesa and Antelope Springs)	Flow, sample (field + lab)
	July-Nov. 2009	New Fork River hydrographs	Transducer data (July-Nov. 2009)
	November 2009	Sample Mesa and Antelope Springs	Flow, sample (field + lab)
	November 2009	Synoptic Flow Study	Flow, sample (field + lab)
	Oct.-Nov. 2009	Install five study wells	Lithology, completion information and diagrams, logs
2010	May-Sep. 2010	Install piezometers and study wells	Lithology, completion information and diagrams, logs
	September 2010	Survey study wells and piezometers, DTW	Location, elevation, LEL, DTW (w/corrected sonic and electronic probe)
	September 2010	Develop study wells	Volumes, rates
	October 2010	GW sampling of AN 11-10D wells	DTW, sample (field + lab), and LLPHC parameters
	October 2010	GW sampling at four artesian wells	Head readings and sample (field + lab)
	November 2010	GW hydrographs	Wells X-1-A, X-1-SW, T-1-RW, and T-1-SW
	November 2010	GW sampling for LLPHC and Data Gaps studies	DTW, sample (field + lab), LLPHC parameters
	December 2010	GW and source characterization sampling for LLPHC	DTW, sample (field + lab), gas, LLPHC parameters
	December 2010	Aquifer testing, four wells	DTW, heads, flow rates, response
2011	June 2011	Continued study well development; aquifer testing, eight wells	DTW, heads, flow rates, response
	June 2011	Sampling of remaining study wells	DTW, sample (field + lab), LLPHC parameters

Notes: GW = groundwater; SW = surface water; DTW = depth to water; LEL = lower explosive limit; LLPHC = low-level petroleum hydrocarbon.

Data collected during these field events, along with data obtained from literature, were used to construct the hydrogeologic conceptual model discussed in **Section 2.0**. Data collected during the execution of AMEC's (2010) sampling and analysis plan, and data obtained from literature, were used to parameterize the solute transport models described in **Section 6.0**.

1.2 Report Organization

This report presents and discusses key components of the numerical groundwater model, including a hydrogeologic conceptual model, numerical model design and calibration, and hypothetical advective and solute transport model results. The report is organized into the following sections:

- **Section 1.0** presents a brief background of the project and the objectives of developing the model.

- **Section 2.0** describes the hydrogeologic conceptual model, including background information on the physical, geological, and hydrogeologic settings of the PAPA; the groundwater budget; aquifer properties; and groundwater quality.
- **Section 3.0** describes numerical model code selection and model design.
- **Section 4.0** describes numerical model calibration and provides calibration statistics.
- **Section 5.0** describes sensitivity analysis performed on the numerical model.
- **Section 6.0** describes results from hypothetical advective and solute transport modeling and uncertainty analysis.
- **Section 7.0** presents a discussion of model limitations.
- **Section 8.0** presents conclusions from the modeling effort.
- **Section 9.0** lists references cited in this report.

Figures and tables are compiled at the end of the report. Appendices A through I present additional supporting data and technical documentation. Several appendices contain detailed technical memoranda or reports that address specific topics, including geologic modeling, groundwater balance calculations, calibration parameters and results, and solute transport parameterization.

2.0 CONCEPTUAL MODEL

This section summarizes available data on the hydrogeologic setting and describes the current understanding (i.e., conceptual model) of the groundwater flow system in the PAPA. This conceptual model forms the basis for the design and construction of the numerical groundwater model discussed in **Section 3.0**. The following subsections summarize the physical, geologic, and hydrogeologic setting of the PAPA. Additional information about the PAPA is presented in Geomatrix (2008b) and AMEC (2012).

The conceptual model described below does not include elements related to contaminant fate and transport. Potential contaminant sources are discussed in detail in AMEC (2010). Selection of parameters related to transport modeling is discussed in **Section 6.0**.

2.1 Physical Setting

The PAPA is located in a broad valley oriented northwest to southeast between the Wind River and Wyoming Mountain ranges (**Figure 1**). The boundary of the numerical groundwater model encompasses the PAPA and is based on hydrologic boundaries (see **Section 3.2.1**). The semiarid climate of the area defines the landscape, which is characterized by rocky soil, sparse vegetation, and numerous ephemeral drainages dissecting ridges and buttes. Topographic elevations range from approximately 6,850 feet above mean sea level (amsl) where the New Fork River exits the PAPA to over 7,700 feet on top of the "Mesa" in the north-central portion of the PAPA. Major drainages include the New Fork River, East Fork River, and Green River (**Figure 2**). Sagebrush communities characterized by shrub-steppe vegetation dominate the PAPA (BLM, 2008a); riparian vegetation and wetlands occupy floodplains of the New Fork and Green rivers.

The PAPA encompasses an area of approximately 309 square miles, and is about 14 miles wide by about 30 miles long. Natural gas exploration and production within the PAPA target natural gas accumulations within a subsurface geologic trap called the Pinedale Anticline. The Anticline Crest is approximately 2 to 3 miles wide, and is oriented northwest to southeast, parallel to the Wind River Range located to the east (**Figures 1** and **2**).

Natural gas exploration and production activities began in the PAPA in 1939 with the completion of the Government 1 well (AMEC, 2010). An additional 20 wells were completed by 1984. Between 1984 and 1993 no new gas wells were installed. Since 1994, natural gas exploration and production activities have increased again due in part to improvements in hydraulic fracturing technologies. Over 2,000 new gas wells have been developed since 1994 and are distributed along the entire length of the anticline crest of the PAPA (**Figure 3**; WOGCC, 2011).

2.2 Geologic Setting

The PAPA is situated in the Upper Green River Basin between the southwest-thrusted Wind River Mountain uplift and the east-thrusted Wyoming thrust belt. The Pinedale Anticline is a thrust-rooted detachment structure about 35 miles long and 6 miles wide, whose axis generally parallels the Wind River Mountains. Law and Johnson (1989) suggest the Pinedale Anticline formed in response to southwest- directed compression associated with the Wind River uplift. Both sides of the anticline are bounded by thrust faults of the Laramide Orogeny: the Pinedale Thrust Fault to the west and the Wind River Thrust

Fault to the east (Govert, 2011). Although Govert (2011) reports that normal faults are associated with the anticline crest, these faults do not appear to be expressed in the thousands of feet of Tertiary-age rock overlying the anticline.

Near-surface geology within and adjacent to the PAPA consists of the Tertiary-age Wasatch Formation (sedimentary rock), unconsolidated glacial outwash along the mountain fronts, terrace gravels on the upland topographic feature known as the Mesa, and alluvial deposits (sand, silt, gravel) along surface water courses (**Figure 4; Table 1**). The Wasatch Formation generally underlies the entire PAPA and was deposited in an internally drained depositional basin contemporaneous with the Green River Formation, which represents lacustrine (lake) deposition. The Wasatch Formation consists primarily of discontinuous, lenticular arkosic sandstone beds representing river channel deposits, and sandy shale and siltstone representing overbank and floodplain deposits (**Figure 5; Table 1**). Based on geologist's logs from wells installed by AMEC (2012), shale is described as hard and massive, and individual grains cannot be distinguished; whereas siltstone is described as fine-grained and poorly cemented, and individual grains can be identified. For modeling purposes, all fine-grained material was grouped together (see **Section 2.2.1**). Due to migration of the lake shoreline over time, sediments from the Wasatch Formation are inter-fingered with deposits from the Green River Formation. The Green River Formation consists predominantly of lacustrine deposits of fine sandstone, siltstone, and shale. Beds in both of these formations are generally horizontal or sub- horizontal, but are typically not described as continuous over large areas (Clarey et al., 2010). The thickness of the Wasatch Formation in the PAPA ranges from approximately 3,000 to 7,000 feet (Chafin and Kimball, 1992; Welder, 1968; Glover et al., 1998; Roehler, 1992; Martin, 1996). The Tertiary-age Fort Union Formation underlies the Wasatch Formation and comprises similar lithology to the Wasatch.

Overlying the Wasatch Formation on the Mesa are coarse alluvial glacial outwash gravels of Quaternary age that originate from the Wind River Range. Based on previous reports (Geomatrix, 2008b; AMEC, 2012), these terrace gravels are approximately 10 to 35 feet thick. Recent alluvial deposits of unconsolidated sand, gravel, and some silt/clay occur in the valleys of the Green River, New Fork River, and their tributaries. Alluvial deposits in the PAPA are typically less than 100 feet thick (AMEC, 2012).

The gas-producing interval in the PAPA includes the upper Cretaceous-age Upper Mesaverde and Lance formations, as well as an unnamed overlying Tertiary-age unit. These units are collectively known as the Lance Pool. These sedimentary units consist of medium- to fine-grained sandstone interbedded with mudstone and siltstone (Govert, 2011). The uppermost gas-bearing units of economic significance are located approximately 8,000 to 12,000 feet or more below ground surface. The Lance Pool is overlain by the Tertiary-age Fort Union and Wasatch formations, which are composed of interbedded conglomerate, sandstone, siltstone, and mudstone. Wasatch Formation sedimentary units described above are relatively horizontal, but discontinuous over large areas (AMEC, 2012).

2.2.1 Geologic Model

AMEC developed a three-dimensional (3D) lithostratigraphic geologic model of the upper approximately 1,100 feet of geologic material in the PAPA using CTech Mining Visualization System (MVS) software (CTech, 2010) (Appendix A). The geologic model domain extends to the Wind River Mountains on the east and to a point below the confluence of the New Fork River with the Green River. The model

covers an area of 1,418 square miles and encompasses the numerical model boundary. Development of the model is described in detail in Appendix A.

The geologic model was created using lithologic data from 243 wells and serves as the geologic framework for the numerical model. Lithologic information extracted from well logs was simplified and categorized to represent near-surface geologic materials in the model. Inspection of well driller's logs, review of geologic literature for the PAPA, and observations made during study well drilling (AMEC, 2012) identified four generalized lithologic categories:

- ***Gravel/fill*** includes the surficial gravel found on top of the Mesa and "fill" material. For the purposes of the geologic model, "fill" is also used to represent surficial geologic materials in high-elevation (e.g., Wind River Range) areas of the model domain where specific lithologic data are unavailable. In order to complete the model, these areas were "filled-in" with unconsolidated material to match the boundaries of the U.S. Geologic Survey [USGS] 10-meter digital elevation model (DEM) and allow aerial imagery to be draped over the model domain.
- ***Unconsolidated material*** represents unconsolidated material reported on driller's logs and alluvial material present in river/steam valleys.
- ***Shale/siltstone*** includes the variety of fine-grained rock units encountered while drilling; part of the Wasatch Formation.
- ***Sandstone*** is part of the Wasatch Formation.

These four lithologic categories were used to construct the geologic model, which was in turn used as the basis for initial parameterization of the groundwater flow model discussed in **Section 3.2.3**.

A variably spaced finite-difference grid was designed for the model that includes finer grid spacing along the axis of the Pinedale Anticline and the central portion of the PAPA along the New Fork River (see **Section 3.2.1**). A geologic hierarchy consisting of 68 layers was generated; lithologic surface contacts were correlated and geologic surfaces interpolated across the site using MVS 3D kriging algorithms. USGS DEM data were used to represent the ground surface. Based on the depth of the deepest industrial water supply well but excluding the Wind River Mountains, the model has a maximum thickness of 1,123 feet. The result of this work presented in **Appendix A** is a 3D volumetric geologic model representing gravel/fill, unconsolidated material, sandstone, and shale/siltstone contacts from the database.

Although developed using sophisticated geostatistical methods, the geologic model reduces the complexity of the geologic system. In regions of the model with greater data density (e.g., along the anticline axis and New Fork River), lithologic "pinch-outs" (i.e., areas where bed thickness tapers to near zero) and layer thicknesses were determined based on interpretation of driller's logs. Lithologic thicknesses from the logs were interpolated into regions of scarce data density (few or absent wells) using MVS 3D kriging algorithms. Four different synthetic data points were generated based on the average thickness and depths determined from geologic cross-sections constructed for the PAPA (AMEC, 2012). Synthetic data points were introduced into regions of the model with low data density. These additional data points were used to constrain the geologic model so the model produced reasonable results in accordance with the conceptual understanding of the hydrostratigraphy. By adding additional points, the kriging algorithms were forced to produce reasonable layer arrangements and thicknesses in regions of the model where lithologic data were

scarce. More variability and less repetition exist in the model in regions where data density is greater, and less variability and more repetition exist in areas with less data density because only four types of synthetic

data points were used. Geologic structure and faulting were not considered when creating the geologic model due to the lack of information regarding structural features and characteristics.

The lateral extent of sandstone layers in the geologic model ranges from about 1,000 feet to 50,000 feet, and the average thickness of sandstone layers is approximately 18 feet. Shale/siltstone layers have lateral extents ranging from about 1 mile to about 40 miles and an average thickness of 33 feet. These model results are consistent with driller's logs and the geologic conceptual model developed for the PAPA. The connectivity between different sandstone and shale units was not evaluated. It was assumed that sandstone units in different wells at similar elevations are connected, unless a well exists between them indicating otherwise. This assumption leads to uncertainty in the model because of sparse data resolution in certain areas of the model, and the lithologic accuracy of the model is only as good as the distance between wells (i.e., greater confidence in model results when wells are close together than when wells are far apart). The geologic model provides an appropriate representative 3D stratigraphic framework for the numerical groundwater flow model based on hydrogeologic data limitations and the scale of the 309 square mile PAPA.

2.3 Hydrogeologic Setting

Groundwater within 1,000 feet of land surface in the PAPA occurs in two principal hydrostratigraphic units (HSU): river alluvial deposits, and Wasatch Formation bedrock. For further discussion regarding the hydrogeologic conceptual model, refer to AMEC (2012).

The Fort Union Formation, which underlies the Wasatch Formation, was not included in the geological or numerical models. The Fort Union Formation is lithologically similar to the Wasatch Formation. According to Clarey et al. (2010), both formations can be considered one large regional hydrostratigraphic unit at a scale greater than 100 miles. For the models described in this report, an increase in litho-static loading from overlying Wasatch Formation sediments was assumed to lead to a decrease in porosity and permeability of the Fort Union Formation (Tetzlaff and Schafmeister, 2007). In addition, groundwater in the Fort Union Formation is approximately 50 to 100 times more saline than Wasatch Formation groundwater (WOGCC, 2011). This difference in salinity would create a density barrier between the two formations as movement of denser, more saline groundwater is restricted by less dense Wasatch Formation groundwater. The Fort Union Formation was not included in the models because both a reduction in porosity and permeability, and a water density barrier, would limit groundwater interaction between the two formations on a scale of less than 30 miles.

2.3.1 Hydrogeologic Units

This section presents a description of the two principal hydrostratigraphic units.

2.3.1.1 Alluvial

Groundwater in the Alluvial HSU is unconfined and occurs in sand and gravel deposits adjacent to principal watercourses in the PAPA. This HSU is hydraulically connected to the underlying Wasatch Formation, as well as to subjacent streams and rivers. Based on study well logs (AMEC, 2012), it is

generally no more than about 30 feet thick (see **Section 2.2**) and is partially saturated. The Wyoming State Geologic Society

(WSGS) (2009a) mapped Quaternary-age alluvial deposits as wide as 3 miles along the New Fork River (**Figures 4** and **6**).

2.3.1.2 Wasatch

Groundwater in the Wasatch HSU primarily flows within sandstone units or lenses that are adjacent to finer grained mudstone or shale/siltstone units. This HSU is characterized as a heterogeneous or compound system, and continuous water-bearing sandstone beds have not been documented over large areas. Based on contrasts in hydraulic conductivity between fine-grained units and sandstone, the discontinuous nature of individual sandstone beds, and hydraulic potentials that commonly rise above the top of the saturated zone, portions of the Wasatch HSU in the PAPA are likely semi-confined.

The Wasatch Formation is not continuously saturated, and in some areas, perched groundwater systems exist that discharge locally to springs. Given the depositional environment of the Wasatch Formation, groundwater in the shallow portion of this unit likely migrates laterally and downward, preferentially in sandstone units, and discharges to springs and rivers or migrates to the deeper saturated zone. Perched groundwater systems were not incorporated into the model because of a lack of data regarding the occurrence, and extent of perched zones as well as the thickness and lateral extent of intermediate unsaturated zones.

Industrial water supply wells that support natural gas exploration and development activities are completed in the Wasatch Formation. Industrial wells are typically completed to depths of less than 1,000 feet with a maximum depth of 1,210 feet and an average of 644 feet. Industrial wells are typically screened across multiple water-bearing sandstone units with reported yields typically in the range of 150 gallons/minute (Wyoming State Engineers Office [WSEO], 2010). Based on well logs from the WSEO database (2010), all but six domestic wells in the PAPA are completed in the Wasatch Formation. The average depth of these domestic wells is about 120 feet (AMEC, 2012).

2.3.2 Groundwater Flow

Groundwater in the PAPA generally flows west and south from the Wind River Mountains and foothills toward the New Fork River (locally) and the Green River (regionally) within the Green River Basin. Some of this water moves along deep groundwater flow pathways in the Wasatch Formation; whereas the remainder moves in shallower flow paths and discharges to springs and rivers (e.g., New Fork River and Green River). Groundwater generally moves horizontally through the various lithologic units (i.e., sandstone, siltstone, and shale) within the Wasatch HSU, with greater flow occurring in the higher permeability sandstone units. Groundwater flow is primarily driven by hydraulic gradients, which are created by higher groundwater elevations in recharge areas along the front of the Wind River Range and lower groundwater elevations at discharge points near the New Fork and Green rivers.

Figure 6 presents a potentiometric surface map for the Alluvial HSU based on groundwater elevation data collected in September 2010. Based on data collected and reviewed for this study, surface water in the New Fork and Green rivers generally gains flow from shallow groundwater hosted in alluvial deposits. The

direction of flow in alluvial deposits is generally parallel to stream flow adjacent to stream channels, but toward the river at the margins of the alluvial deposits.

Figure 7 is a potentiometric surface map for the Wasatch HSU based on September 2010 groundwater elevation data. Based on the geologic setting described in **Sections 2.2** and **2.3**, and observed artesian flow in wells screened in the Wasatch HSU, it is assumed that the potentiometric surface in **Figure 7** does not represent the water table but instead represents the potential head in the aquifer. The potentiometric surface generally reflects regional topography, with steeper hydraulic gradients in recharge areas along the Wind River mountain front than in discharge areas along the major drainages. Groundwater in the Wasatch HSU in the northern portion of the PAPA flows southward toward the New Fork River. A groundwater divide is present south of the New Fork River in the central portion of the PAPA. Groundwater north of this divide flows to the north toward the New Fork River. South of this hydraulic divide, groundwater flows west-southwest toward the Green River and the lower end of the New Fork River.

Groundwater in the shallow portion of the Wasatch HSU over much of the PAPA flows vertically down to the underlying Wasatch HSU under varying degrees of saturation (see **Section 2.3.1.2**). In areas of groundwater recharge, such as along losing reaches of steams in the foothills of the Wind River Range, groundwater moves down from alluvial deposits into the underlying Wasatch HSU. In areas of groundwater discharge, such as along gaining river reaches, groundwater in the underlying Wasatch HSU flows up into alluvial deposits and alluvial groundwater discharges to surface water. Vertical flow also occurs across the various inter-layered units within the Wasatch HSU.

Groundwater in the Wasatch HSU flows through the aquifer preferentially in the higher permeability sandstone units. Groundwater flow through shale/siltstone and sandstone units will be different when considering local versus regional scales. Regionally, groundwater flow paths could be longer than each lithologic deposit such that the least conductive unit (shale/siltstone) that groundwater flows through will limit total flow and velocity. Faults, bedding planes and joints/fractures in Wasatch Formation sandstone, shale/siltstone, and mudstone units may form preferential pathways for groundwater flow. Locations of potential preferential pathways have not been identified due to lack of information regarding faults and fractures within the Wasatch Formation and their potential hydraulic properties. Vertical flow in response to differences in hydraulic head potential also occurs across the various inter-layered units, with the potential for preferential movement along joints/fractures, if present.

Groundwater hydrographs presented by AMEC (2012) indicate that for the period of record (November 2010 to June 2011), groundwater elevations fluctuated approximately 2 feet in alluvial wells. An alluvial well adjacent to the upper New Fork River exhibited a rising water level from March through April 2011, possibly in response to the beginning of spring recharge from the upper New Fork River. Water levels in wells completed in the Wasatch HSU did not exhibit any discernible trends over the period of record investigated (November 2010 to June 2011).

2.3.2.1 Groundwater Gradients and Average Velocity

Figure 6 shows a potentiometric surface map for groundwater in the Alluvial HSU. Where groundwater elevation contours are closer together, horizontal hydraulic gradients are higher; where contours are further apart, gradients are smaller. Horizontal gradients in the Alluvial HSU range between about 0.0038 feet/foot near the town of Pinedale to 0.0014 feet/foot along the New Fork River corridor south of the Mesa. Groundwater elevations and gradients in alluvial deposits are influenced by interaction with

surface water. Variability in horizontal gradients for the Alluvial HSU reflect changes in land surface topography and subsequent surface water stage. As the New Fork River valley flattens away from the Wind River Mountain Range, horizontal gradients decrease.

Figure 7 shows a potentiometric surface map for groundwater in the Wasatch HSU. The horizontal hydraulic gradient in the Wasatch Formation ranges from about 0.013 feet/foot south of Pinedale to 0.0009 feet/foot on the Mesa. Areas in the Wasatch HSU with higher gradients are interpreted to be a reflection of recharge and/or lower transmissivity, whereas areas with lower gradients are interpreted to be areas with higher overall transmissivity.

Vertical groundwater gradients help identify discharge and recharge areas for the groundwater system. Based on gradients measured by AMEC (2012), the lower New Fork River valley is a principal discharge area for groundwater in both the Alluvial and Wasatch HSUs (i.e., upward vertical gradients). Although the New Fork River is a principle discharge point in the system, not all groundwater reaches the river because of semi-confining conditions that exist in the aquifer; a portion of total groundwater flow moves in the Wasatch HSU beneath the river as underflow. Upward vertical hydraulic gradients in this area range from 0.06 feet/foot to 0.14 feet/foot between the Wasatch HSU and Alluvial HSU (**Figure 6**) and from 0.06 feet/foot to 0.22 feet/foot between shallow and deep intervals of the Wasatch HSU (**Figure 7** and **Table 2;** AMEC, 2012). Vertical gradients were calculated for paired wells and it was assumed that the aquifer is continually saturated between screened intervals.

In the upper reaches of the New Fork River, groundwater hydrographs show generally an upward gradient from the Wasatch HSU to the Alluvial HSU, although the gradient does reverse at times. Vertical hydraulic gradients measured between the Wasatch HSU and Alluvial HSU in the north end of the PAPA had downward vertical hydraulic gradients of 0.001 feet/foot to 0.003 feet/foot in September 2010, and upward gradients of 0.012 feet/foot to 0.016 feet/foot in June 2011 (**Figure 6**) (AMEC, 2012). Seasonal fluctuations in vertical groundwater gradients were not simulated because the model represents average annual conditions and is not capable of simulating transient changes (see **Section 3.0**).

Areas of recharge to the Wasatch HSU (i.e., downward vertical gradients) are apparent at the north end of the PAPA and in the Warbonnet and Antelope areas (**Figures 6** and **7**) (AMEC, 2012). Downward vertical hydraulic gradients between paired Wasatch bedrock study wells range from 0.02 feet/foot to 0.37 feet/foot (AMEC, 2012).

AMEC estimated and tabulated average groundwater velocity in alluvial deposits and in Wasatch Formation sandstone units from aquifer testing (see **Section 2.4**; AMEC, 2012). Estimates range from 1,390 feet/year to 4,270 feet/year in alluvial deposits and from 0.011 foot/year to 40 feet/year in sandstone (AMEC, 2012).

Vertical and lateral discontinuities in sandstone units will have an effect on average linear groundwater velocities. Although calculated groundwater gradients are based on the interpreted potentiometric surface and take into account lateral and vertical lithologic discontinuities, other components of the velocity equation do not (AMEC, 2012). Lateral lithologic discontinuities can exist at a scale of less than 1,000 feet (or less than model cell size [see **Section 3.0**]), and vertical lithologic discontinuities can exist on a scale of 5 feet or less (AMEC, 2012). Because shale/siltstone units have lower hydraulic conductivity relative to sandstone, there is a potential that water in discontinuous sandstone units may be retarded and, at a basin scale, there is a possibility that groundwater could move slower than the values presented above. In addition, although there is a lack of information regarding jointing/fracturing of the Wasatch Formation,

there is a possibility that groundwater flow could exploit these potentially higher conductivity features, resulting in greater groundwater velocities than estimated assuming these features are interconnected and act as conduits to groundwater flow. **Section 6.0** of this report discusses velocities with respect to contaminant transport modeling and presents velocities simulated by the numerical model assuming no faults or fractures are present in the aquifer.

2.3.2.2 Groundwater Recharge and Discharge

Most groundwater recharge occurs along the north and east side of the PAPA along the front of the Wind River Mountains. Water flowing off the mountains recharges shallow alluvial systems on tributary streams draining the mountains, which in turn recharge the underlying Wasatch bedrock flow system. Other sources of groundwater recharge include stream loss from reaches of the New Fork and Green rivers, irrigation ditch loss, recharge from irrigated lands, and precipitation. Due to topographic positions, the Mesa, Ross Ridge, and Blue Rim receive more recharge than lower elevation portions of the PAPA.

The primary zone of groundwater discharge is to streams. Other points of discharge include evapotranspiration (ET) from wetlands and phreatophytes in riparian zones, groundwater underflow out of the PAPA, and pumping from wells (smallest component of discharge). **Section 2.5** presents the groundwater balance for the numerical model domain.

2.4 Aquifer Properties

In 2006, Geomatrix conducted a single-well, step-drawdown test on the North Mesa 4-7 (AMI140) industrial water supply well. Based on results of that test, Geomatrix estimated a transmissivity of 128 feet^2/day and a hydraulic conductivity of 2.78 feet/day, for the water-bearing sandstone units of the Wasatch HSU in which the well is completed.

In 2010 and 2011, eleven constant-discharge tests and one constant-discharge shut-in test were performed by AMEC on selected study wells in the PAPA to evaluate the hydraulic response of the different HSUs to pumping (AMEC, 2012). The first set of aquifer tests was completed on four wells in December 2010, and the second set of tests was completed on eight wells in June 2011. Results of the tests are summarized in **Table 3,** and well locations are shown on **Figures 6** and **7**. Tests extended for periods ranging from

hours to 18 hours at pumping rates ranging from 6.1 gallons/minute to 53 gallons/minute. Pressure transducers were installed in the pumping well and any nearby observations wells, if present. All wells tested were screened in water-bearing sandstone units and were developed prior to testing.

Results of aquifer testing show that hydraulic conductivity of the various lithologic units screened is highly variable. Hydraulic conductivity (*K*) and transmissivity (*T*) determined from recovery data for the 12 aquifer tests shows the following results (**Table 3; Figures 6** and **7**):

- Alluvial HSU (1 well tested): K = 446 feet/day; T = 11,144 feet^2/day;
- Regional Wasatch HSU (10 wells tested): K = 0.02 to 9.5 feet/day; T = 1.6 to 264 feet^2/day.

Independent hydraulic conductivity values from 270 estimates in the Wasatch Formation ranged from 0 foot/day to 2,106 feet/day (Clarey et al., 2010).

Drawdown responses were not observed in any of the observation study wells during the six pumping tests for well pairs. The lack of drawdown response in the observation wells during the pumping tests, with one exception noted below, may be the result of pumping in high-permeability material, low pumping rate, differences in screened intervals between pumping and observation wells, and/or low-permeability material separating the two well screens. The absence of response in observation wells indicates limited hydraulic communication between the individual lithologic units in the tested locations.

The one observation well that exhibited a drawdown response during a pumping test was industrial water supply well AN11-10D during the test of well T-4-RW-b (AMEC, 2012). This observation well exhibited

19.75 feet of drawdown during the pumping test. Well AN11-10D (located approximately 170 feet north-northwest of T-4-RW-b) is perforated from 470 to 660 feet below ground surface (bgs), across several water-bearing sandstone units in the Wasatch HSU. Study well T-4-RW-b is screened at a depth (637 feet to 656 feet bgs) that corresponds to the lower end of the perforated interval in AN11-10D, and is likely screened in part of a sandstone unit common to both wells. Further information regarding aquifer test results is presented in AMEC (2012).

Natural variability in hydraulic conductivity for a shale/siltstone and sandstone aquifer can range over several orders of magnitude (Bear and Cheng, 2010). Spatially, sandstone layers are continuous up to a few thousand feet, while shale/siltstone layers are continuous up to several miles (see **Section 2.2.1**). This natural spatial variability in aquifer material results in large variability in hydraulic conductivity. Results obtained from aquifer tests performed by AMEC reflect some but not all of this variability, because the wells tested were screened across mostly coarse-grained, sandstone units.

2.5 Groundwater Balance

This section discusses water balance components for the groundwater system in the model region. **Appendix B** presents the equations and values used for calculating each component of the groundwater balance. The groundwater balance, which includes only components of flow entering and exiting the saturated subsurface, will be used as the basis for numerical model flux boundaries and is described by Equation 1:

$$\text{Inflow} = \text{Outflow} \pm \text{Change in Storage} \qquad \text{(Equation 1)}$$

A steady-state groundwater balance (Figure 8) was developed to provide a basis for simulating steady-state flow conditions in the numerical groundwater model. The steady-state groundwater balance is based on annual average conditions except for base flow to streams; base flow to streams is based on November conditions, because this month is representative of average base flow conditions (i.e., after the irrigation season and the runoff period). Using this period also allows use of synoptic flow data from November 2009 (AMEC, 2012).

The steady-state groundwater balance can be expressed by Equation 2, which is based on significant sources of groundwater recharge and discharge within the model region:

$$R_N + R_I + R_D + U_{in} = BF + U_{out} + G_{pump} + ET \qquad \text{(Equation 2)}$$

Where:

R_N = natural recharge
R_I = irrigation recharge RD = ditch loss recharge
U_{in} = groundwater underflow into the model region
BF = groundwater discharged to rivers and streams (base flow)
U_{out} = groundwater underflow out of the model region
G_{pump} = groundwater pumped for consumptive use (groundwater not returned to the aquifer)
ET = evapotranspiration directly from the saturated zone

Table 4 presents estimated flow rates for each component of the groundwater balance. The following subsections and **Appendix B** describe how the estimated values shown in **Table 4** were developed using data collected historically and during this investigation. Differences between total inflow and outflow can be attributed to differences between estimated values versus actual values or to changes in groundwater storage related to changes in water table elevations. The water table is the surface of an unconfined aquifer at which pore pressure is atmospheric.

2.5.1 Recharge

Average annual precipitation across the model region ranges from 8 inches/year to 14 inches/year based on average annual precipitation from 1971 to 2000 (PRISM Group, 2008). Precipitation in the mountains northeast and west of Pinedale is significantly greater than that of the lower elevation portions of the model region.

Measuring natural recharge is difficult; however, studies by Martin (1996) and Hammerlick and Arneson (1998) attempted to map estimated recharge across the region (**Figures 9** and **10**). These studies indicate that the primary recharge to Tertiary-age aquifers occurs along the basin margins where the formations are exposed at land surface and precipitation rates are greatest. The mapped recharge rates across the model region were used to calculate the range of volumes of natural recharge. Natural recharge values for the model region range from approximately 7,600 acre-feet/year to 12,600 acre-feet/year, with an average of approximately 10,000 acre-feet/year.

In addition to natural recharge, some recharge occurs from deep percolation of irrigation water that passes below the root zone. Martin (1996) estimated recharge rates ranging from 2 inches/year to 2.5 inches/year in an irrigated region around Farson-Eden, Wyoming, southeast of the PAPA. This range was applied to the areas of irrigated land within the model region, resulting in an irrigation recharge rate ranging from approximately 5,900 acre-feet/year to 7,300 acre-feet/year **(Appendix B)**.

2.5.2 Groundwater Underflow into Region

A significant amount of water enters the model region as groundwater underflow from the north and east. Underflow into the model region was calculated using Darcy's Law (Equation 3):

$$Q = K\,I\,A \qquad \text{(Equation 3)}$$

Where:

Q = flux
K = hydraulic conductivity
I = gradient
A = cross-sectional area

Underflow rates were estimated using the range of hydraulic conductivity values measured within the PAPA for the different HSUs (**Table 3** and **Section 2.4**). Average hydraulic gradients were estimated for each boundary based on the potentiometric surfaces presented in **Figures 6** and **7**. The cross-sectional area was based on the width of the boundary and the saturated thickness. The saturated thickness was calculated as the water table elevation subtracted by the base elevation of the Wasatch Formation, which was extrapolated from a geologic cross-section (Scott and Sutherland, 2009). The elevation at the base of the Wasatch Formation was 3,000 feet amsl for the upgradient boundary and 4,600 feet amsl for the downgradient boundary.

Groundwater underflow is anticipated through three dominant lithologic materials: alluvial deposits, glacial outwash, and the Wasatch Formation. The underflow boundary was divided into components using the thickness and length of each saturated HSU. Hydraulic conductivity ranges for each lithology were applied to the cross-sectional area for each lithologic unit. Using minimum and maximum hydraulic conductivity values, underflow into the model region ranges from 95,086 acre-feet/year to 345,690 acre-feet/year, with an average of approximately 220,400 acre-feet/year **(Appendix B**).

2.5.3 Irrigation Ditch Loss

Irrigation ditches were located and digitized using topographic maps and satellite imagery. Data from the "Upper Green Normal" surface water model (AECOM, 2009) were used to determine the annual volume of water diverted from rivers into the respective irrigation ditches. Diversion data from each river segment were compiled and applied to each ditch in the segment. Based on the volume of water diverted and the length of ditches within the model region (167 miles), total annual ditch flow in the region is estimated at approximately 48,600 acre-feet/year. This value does not account for 19.5 miles of ditches for which no flow data were available. However, the estimate of 48,600 acre-feet/year provides a ceiling limit on any calculations of ditch loss.

Total ditch loss estimates were evaluated based on a review of literature. Seven investigations of ditch loss within western North America were reviewed, including studies in Montana, Texas, California, Oklahoma, Wyoming, and Alberta (PBS&J, 2008; Montana DNRC, 2003; Leigh and Fipps, 2002; Quinn et al., 1989; Nofziger et al., 1979; Nelson Engineering, 2004; Iqbal et al., 2002). Four of these studies allowed for estimation of seepage loss in acre-feet/year per mile of ditch. Two studies allowed for estimation of seepage as a percent of total flow per mile of ditch, and one study (Iqbal et al., 2002) allowed for estimation of

seepage as a volume per ditch area per day (**Table 5**). Seepage rates from each study were applied to the lengths and/or areas of ditches in the model region, resulting in estimated ditch loss volumes within the model region (**Table 5**).

The average seepage rate from Iqbal et al. (2002) (0.07 cubic feet [feet^3] per square foot per day) was applied to the average 137-day irrigation season for the Green River Basin as documented by AECOM (2009). Since the total ditch loss estimate from the PBS&J (2008) study yielded a value greater

than the estimated total annual flow in the ditches (48,600 acre-feet/year), this estimate was eliminated from the range of feasible values. Minimum, maximum, and average losses for total ditch length based on loss estimates from these six studies results in ditch loss estimates ranging from approximately 1,303 acre- feet/year to 43,141 acre-feet/year, with an average estimate of approximately 16,128 acre-feet/year (**Appendix B**).

2.5.4 Groundwater Discharge to Rivers and Streams (Base Flow)

Streams and rivers in the model region have gaining and losing reaches. Where streams flow from high elevations with higher precipitation across alluvial fans or terrace deposits, surface water loss may occur as surface flow infiltrates into the coarse-grained, unconsolidated deposits. However, in the valley floor along the major rivers, surface water gains flow where local and regional groundwater system discharge to the water bodies. Net groundwater discharge to surface water was estimated for seven streams: Green River, New Fork River, East Fork River, Big Sandy River, Pine Creek, Pole Creek, and Boulder Creek (**Figure 8**). Synoptic stream gaging was conducted along the New Fork River and its tributaries on November 5 and 6, 2009 (AMEC, 2012). Flow data for streams and rivers that were not part of the synoptic survey were obtained from the National Water Information System (USGS, 2011). If available, data from November 5 and 6, 2009, were used for streams not gauged as part of the synoptic study; otherwise the average November flow rate was used.

For each stream, discharge data from the upstream location, along with any tributary flow, was subtracted from the downstream location. The difference in discharge was then divided by the catchment area between gauging stations minus any tributary catchment area, resulting in a base flow per catchment area ratio for each stream. This ratio was then multiplied by the catchment area within the model region for each stream to obtain the estimated base flow (**Table 6**). Boulder Creek has a net loss across the model region. It appears to behave as a losing stream; this is likely a result of significant flows being released out of Boulder Lake that are lost into the glacial and alluvial fan deposits that underlie the creek. The estimated base flow contribution to streams and rivers within the model region ranges from 160,981 acre-feet/year to 241,472 acre-feet/year with an average of approximately 201,200 acre-feet/year **(Appendix B**).

2.5.5 Groundwater Underflow out of Region

A moderate amount of water exits the model region as groundwater underflow to the south (Figure 8). Underflow was calculated using Darcy's Law as described for the calculation of underflow into the model region (see Section 2.5.2; Equation 3). For the downgradient boundary, saturated thickness was estimated based on the water table elevation and an elevation of 3,000 feet amsl at the base of the Wasatch Formation. Using minimum and maximum hydraulic conductivity values for each HSU, groundwater underflow out of the model region ranges from approximately 4,400 acre-feet/year to 34,400 acre-feet/year, with an average of approximately 19,400 acre-feet/year (Appendix B).

2.5.6 Groundwater Pumped for Consumptive Use

Groundwater in the model region is pumped for agricultural, domestic, and industrial uses. This consumptive water use makes up a minor component of the groundwater balance. According to the WSEO (2010) groundwater well database, nine irrigation wells, 145 stock wells, 1,076 domestic/other wells, and 366 industrial water supply wells are present within the model region.

Estimates of consumptive groundwater use from irrigation and stock wells were based on data from Ahern et al. (1981), which were reproduced by Clarey et al. (2010). According to these data sources, the average annual groundwater volumes used in the Green River Basin are 66 acre-feet/year for individual irrigation wells and 0.6 acre-feet/year for stock wells. Multiplying these rates by the number of irrigation and stock wells results in volumes of 595 acre-feet/year and 88 acre-feet/year, respectively. Each well coded as domestic or other was assumed to supply one household with an average of 2.47 persons, based on the average household size in Wyoming (U.S. Census Bureau, 2010). Assuming an average per capita use of 75 gallons/day (USGS, 2006) results in 223 acre-feet/year for the 1,076 domestic/other wells. Previous studies have shown that consumptive use constitutes only 2.3 to 3.2 percent of pumped domestic water (Kimsey and Flood, 1987). Based on a conservative industry standard, it was assumed for this groundwater balance that 10 percent of domestic groundwater withdrawals represent consumptive use, and the remaining 90 percent becomes return flow, resulting in 22 acre-feet/year consumed by domestic/other wells.

Of the 366 industrial water supply wells, groundwater consumption records were available for 238 of the wells. Based on the available well data, an average of 20 percent of the industrial supply wells are actively in use; of those, the average amount of water consumed per well is 7 acre-feet/year (based on consumptive use data from Operators for 2008-2010 as reported annually to BLM). Extraction from recorded wells totaled 415 acre-feet/year. Assuming 20 percent of the remaining 128 wells are pumped at 7 acre-feet/year results in an additional 175 acre-feet/year, resulting in an estimated total extraction rate of 590 acre-feet/year for all industrial water supply wells.

Combining these estimates produces a total estimated consumptive groundwater volume of approximately 1,300 acre-feet/year pumped annually from irrigation, stock, domestic/other, and industrial water supply wells in the model region **(Appendix B**).

2.5.7 Evapotranspiration from Groundwater

Evapotranspiration from groundwater was estimated by applying mean potential ET (PET) to the area covered by wetlands within the model region, and assuming an ET rate of zero in non-wetland areas. ET is defined as the sum of evaporation from groundwater and transpiration from plants, and PET is defined as the ET that would occur under given climatic conditions if there were unlimited soil moisture (Fetter, 2001). Wyoming's mean annual PET in the Sublette County area ranges from less than 43 centimeters (16.9 inches) to 48 centimeters (18.9 inches) (Marston, 1990). Based on this information, a range of PET values (15 to 20 inches) was applied to the area of wetlands (U.S. Fish and Wildlife Service, 2009). A range of wetland areas (33,089 to 35,425 acres) was assessed by alternatively including and removing ponds and river areas from the area considered wetlands. Using these assumptions, ET directly from groundwater was estimated to account for between 41,361 acre-feet/year and 59,042 acre-feet/year, with an average of approximately 50,201 acre-feet/year (**Appendix B**).

2.6 Groundwater Quality

Based on SCCD water quality data collected between 2004 and 2011, water quality in the PAPA is generally characterized by low to moderate concentrations of dissolved solids. Average concentrations of total dissolved solids (TDS), chloride, fluoride, and sulfate generally trend higher with depth. Chloride, fluoride,

sulfate, and sodium adsorption ratio (SAR) exceed applicable standards in some industrial water supply wells (AMEC, 2012).

Clarey et al. (2010) evaluated natural water quality from 336 wells and 48 springs in the Wasatch Formation in the Greater Green River Basin. In comparison to Wyoming water quality standards (WDEQ, 2005) for Class I water (suitable for domestic use), the study found that samples exceed the standards for several parameters: pH (60 percent of sample locations exceeded upper limit of 8.5 standard units), TDS (40 percent), sulfate (25 percent) and chloride (3 percent). SAR exceeded the standard for agricultural use in 72 percent of the Wasatch Formation water samples. Clarey et al. (2010) present possible natural sources of exceedances for several of these parameters:

- Sulfate – The likely source is evaporate minerals (e.g., gypsum) deposited in closed lake basins during arid intervals of the Tertiary geologic period.
- Fluoride – The likely source is volcanic ash and tuff incorporated into geologic deposits during deposition.
- TDS – Concentrations tend to be high given the arid climate and small rate of recharge in much of the Greater Green River Basin.

AMEC (2012) collected and analyzed water quality data for surface water and groundwater in the PAPA and reached the following conclusions:

- Surface water in the New Fork River is a calcium-carbonate-bicarbonate type, with the upstream reach of the river having the greatest ionic strength. The river water is likely being "diluted" with higher quality water downstream as several primary tributary channels (e.g., Pine Creek, Pole Creek, Boulder Creek, and East Fork River) join the New Fork River within the PAPA.
- Groundwater in the PAPA is represented by several water types:
    - Groundwater in the Alluvial HSU is calcium-carbonate-bicarbonate type, similar to water in the New Fork River, except for one sample: water from well X-4-A is a sodium-carbonate-bicarbonate type.
    - Groundwater samples from the study wells in the Wasatch HSU are a sodium-carbonate-bicarbonate type, with the remaining six wells having sodium-sulfate-type water. Two of the Wasatch HSU wells (T-3-RW and T-6-SW) also have elevated concentrations of chloride.
- None of the analytical results for groundwater samples from Alluvial HSU study wells exceeded the maximum contaminant level for Wyoming DEQ water quality standards for pH, TDS, chloride, sulfate, fluoride, and SAR (Wyoming DEQ, 2005). Analytical results for some groundwater samples from the 18 Wasatch HSU study wells exceeded water quality standards for pH (14 wells exceed pH of 9.0), TDS (3 wells), chloride (2 wells), sulfate (2 wells), fluoride (5 wells), and SAR (19 wells).

3.0 CODE SELECTION AND MODEL DESIGN

This section describes the selection of the computer code used to develop the numerical model as well as model design features, such as the model domain and discretization, boundary conditions, and selection of initial hydrologic model inputs. During model construction, BDE, the Operators, and AMEC held web-based and face-to-face meetings on five occasions between May and August 2011 to discuss model design and implementation of boundary conditions.

3.1 Code Selection

The computer code MODFLOW-SURFACT (HydroGeoLogic Inc., 1996) was selected for the project because it has all the required capabilities for the study based on modeling objectives, the size and complexity of the project area, and hydrologic features expected to affect groundwater flow within the study area. MODFLOW–SURFACT is a fully integrated flow and transport code based on the USGS groundwater modeling software, MODFLOW (Harbaugh et. al., 2000). MODLFOW-SURFACT provides additional modules to MODFLOW to improve its robustness and increase its physical simulation capabilities. These additional capabilities include complex saturated-unsaturated subsurface flow analysis, and contaminant fate and transport calculations. In comparison to MODFLOW, MODFLOW-SURFACT offers the following additional capabilities:

- Ability to accommodate conditions of desaturation/resaturation of aquifer systems;
- Additional robust numerical and matrix solution techniques for complex problems;
- Saturated-unsaturated modeling of water flow;
- Saturated-unsaturated modeling of air flow; and
- Enhanced solute transport capabilities compared to MT3D (Zheng and Wang, 1999), a solute-transport code commonly used with MODFLOW.

MODFLOW-SURFACT flow output can be used by MODPATH (Pollock, 1994) for particle tracking, and by MODFLOW-SURFACT's transport module to simulate contaminant transport. The graphical-user-interface Groundwater Vistas Version 6 (Rumbaugh and Rumbaugh, 2011) was used to create model input files and evaluate results.

3.2 Model Design

This section discusses numerical model design elements, including the model region, grid discretization, boundary conditions, and preliminary input parameters. The conceptual model (see **Section 2.0**) served as the basis for the elements of the numerical model.

3.2.1 Model Domain and Grid Discretization

The model domain is 547 square miles inclusive of the PAPA boundary (**Figure 1**). The margins of the model domain are based on hydraulic boundaries. The model is bounded to the west by the Green River and to the south by a hydraulic divide and an underflow boundary defined by a potentiometric

contour. To the east, the model is bound by the Big Sandy River and to the northeast by an underflow boundary defined by a potentiometric contour.

The model grid is rotated 34 degrees to the west to align with general directions of groundwater flow and includes variable spacing to provide additional detail along the axis of the anticline and the New Fork River. Grid spacing ranges from 300 to 2,006 feet, and the model contains 205 rows, 171 columns, 69 layers, and 2,418,795 cells (**Figure 11**). The upper 68 layers of the model were defined by lithologic modeling incorporating data from 243 wells (see **Section 2.2.1** and **Appendix A**). In general, the model layers represent alternating units of shale/siltstone and sandstone. However, many of the sandstone units pinch out, and thus many of the model layers containing sandstone lenses include zones with shale/siltstone (**Figure 12**). The deepest layer (Layer 69) of the model incorporates the majority of the Wasatch Formation and represents sandstone and shale/siltstone. Layer 69 extends down to an elevation of 3,000 feet amsl, which is the approximate base of the Wasatch Formation across most of the domain and thins to the east toward the Wind River Range. The bottom elevation of Layer 69 was extrapolated from the geologic cross-section depicted by Scott and Sutherland (2009). Layer 69 is used to simulate deep flow paths within the Wasatch Formation; hydraulic conductivity for this layer was determined during the calibration process, because no data are available below the deepest industrial water supply well. In order to have generally horizontal layers representing the generally horizontal stratigraphy, portions of the upper model layers are above ground surface. The model cells in portions of layers that are above ground surface are defined as inactive (no-flow).

3.2.2 Boundary Conditions

Hydrologic boundary conditions are simulated using various MODFLOW-SURFACT packages. Types and locations of the boundary conditions are shown on **Figure 13** and summarized in the following subsections.

3.2.2.1 General Head Boundaries

Underflow into and out of the model domain is simulated with MODFLOW's General Head Boundary (GHB) Package. The GHB Package is a head-dependent boundary condition used in groundwater modeling to allow groundwater to flow in or out of a model according to a regional gradient or from a surface water body. GHB cells are assigned both a head (groundwater level) value and a conductance value that describes how easily water flows in or out of a model cell. The conductance value is calculated based on the width (*w*), hydraulic conductivity (*K*), thickness of the interface between the feature the GHB represents and the groundwater system (*t*), and the distance to the boundary (*D*) (Equation 4).

$$C = \frac{Ktw}{D} \qquad \text{(Equation 4)}$$

Where:

C = conductance (feet^2/day)
K = hydraulic conductivity (feet/day)
t = thickness feet)
w = width (feet)
D = distance (feet)

The flow rate (Q) in or out of the model to or from the GHB is then determined by the conductance value and the magnitude of the difference between the head assigned to the GHB and the simulated head in the model cell (Δh) (Equation 5).

$$Q = C\Delta h \qquad \text{(Equation 5)}$$

Where:

Q = flow rate (feet^3/day)

C = conductance (feet^2/day)

Δh = difference in head (feet)

GHB cells representing mountain front recharge entering the model domain as underflow from the northeast were placed along the edge of the model at the inferred location of the 7,220-foot equipotential contour on **Figure 7**. This contour was estimated based on surface water elevations shown on the USGS Boulder Lake topographic quadrangle map and on groundwater elevations from USGS's National Water Information System (USGS, 2011). It is assumed that mountain front recharge supplies water to the upper layers of the model. Active boundary cells above Layer 27 were assigned GHB boundary conditions with a head of 7,229 feet, which is the estimated head 2,000 feet upgradient of the 7,220-foot contour. Therefore, the distance to the GHB head was set at 2,000 feet; GHB hydraulic conductivity values were assigned based on the hydraulic conductivity of adjacent cells; and the area and thickness of each GHB boundary was set equal to the cell size.

GHB cells were placed along the edge of model domain at the inferred location of the 6,920-foot equipotential contour (**Figure 7**) in all saturated layers along the downgradient margin (Layers 33-69) to represent underflow leaving the model domain. Boundary heads at the water table are set to 6,910 feet, which is the estimated head 2,000 feet downgradient of the 6,920-foot equipotential contour. Therefore, the distance to the GHB head was set at 2,000 feet. Head values were assigned to GHB cells in layers deeper than the water table decreasing with depth to establish a 0.01 feet/foot downward vertical gradient. The vertical gradient is based on field-measured vertical gradients in that area (**Figure 7**). Boundary hydraulic conductivity values are based on the hydraulic conductivity of adjacent cells, and the area and thickness of the boundary was set equal to the cell size.

3.2.2.2 River, Streams, and Ditches

Rivers, streams, and irrigation ditches are simulated using MODFLOW's River Package. The River Package is a head-dependent boundary that allows for flow between groundwater and surface water features. River package cells simulate interaction between groundwater and surface water based on the surface water stage at the boundary, head in the adjacent aquifer, and conductance of the boundary. Stream and ditch stage elevation was set based on elevations from USGS topographic quadrangles. Conductance is defined by the thickness and hydraulic conductivity of the stream/ditch bed and the wetted cross-sectional area of the stream or ditch. The River Package cells representing rivers and streams were assigned widths based on estimates from aerial photos (**Table 7**). The width of ditches was assigned based on aerial photographs and field photos or was estimated based on discharge (**Table 8**). Stream or ditch widths equal the digitized

width within a model cell. Initial streambed hydraulic conductivity values were assigned based on estimates of grain size and the corresponding literature estimates of conductivity (Lapham, 1989; Song et al., 2010). These values were then adjusted during the calibration process (see **Section 4.2**).

3.2.2.3 Recharge

Areal recharge and deep percolation from irrigation are simulated using MODFLOW's Recharge Package (**Figure 14**). Areal recharge was simulated based on estimates from Hammerlick and Arneson (1998). Higher elevation areas, including the Mesa and foothills of the Wind River Range, receive more precipitation and, therefore, are assigned higher recharge rates. Coarse-grained, high-permeability alluvial deposits along the river corridors are also assigned higher recharge rates because precipitation can more easily infiltrate to groundwater through coarse-grained soils than through finer grained upslope soils. Recharge from deep percolation associated with irrigation was assigned to areas of irrigated land, with recharge estimates based on work by Martin (1996). Recharge rates for the model range between 0.09 inch/year and 5.6 inches/year and account for approximately 4 percent of the overall groundwater balance.

3.2.2.4 Evapotranspiration

Evapotranspiration from the area of mapped wetlands (U.S. Fish and Wildlife Service, 2009) is simulated using MODFLOW's ET Package (**Figure 15**). The ET Package is used to simulate the effect of plant transpiration and direct evaporation from groundwater. Each ET Package cell is assigned an ET rate and an extinction depth. The assigned ET rate is 17.5 inches/year based on the estimated PET rate for the area from Marston (1990), and the extinction depth was set to 5 feet based on the approximate extinction depth of grass in sandy soils (Shah et al., 2007). Based on field observations by AMEC and geologists logs for wells completed in the river valleys (AMEC, 2012), grass in sandy soils provided the best match for soil and vegetation types reported by Shah et al. (2007). If depth to groundwater becomes greater than the extinction depth, the ET boundary no longer removes groundwater from the system. Based on the simulated extinction depth of 5 feet and depth to groundwater in the model, ET boundary conditions outside of alluvial deposits along the New Fork and Green rivers do not affect model results.

3.2.2.5 Wells

Sixty-one pumping wells were simulated in the model using MODFLOW-SURFACTS's Fracture Well (FWL4) Package, with pumping rates set at values supplied by the Operators (**Table 9**). The FWL4 Package, an alternative to MODFLOW's Well Package, was selected because of its capabilities to simulate flow in multi-layer wells. Total withdrawal from a well is calculated by the FWL4 Package using modeled transmissivity values for the different model layers containing the screened interval (see **Section 4.3**).

Domestic and stock wells were not simulated because their consumptive use is a small component of the groundwater balance (<0.5 percent) (AMEC, 2012).

3.2.3 Initial Hydraulic Conductivity

Hydraulic conductivity was assigned using hydrogeologic zones. Hydrogeologic zones are areas where hydraulic parameters are spatially constant. In reality, hydraulic properties in the different hydrogeologic zones are not spatially constant. However, because available data are limited, this simplifying assumption was made. Initial zones were established using surface and bedrock geologic maps (Figures 4 and 5) and

results from the geologic model (see Section 2.2.1). Where the geologic model produced layers that were less than 0.5 foot thick, the hydrogeologic zone was assigned hydraulic properties identical to the hydrogeologic zones above and below in order to simulate a pinch out of a sandstone unit (Figure 12).

Six zones were established representing different geologic units identified in the model domain: Mesa Terrace gravel deposits; glacial outwash; alluvial deposits; Wasatch sandstone; Wasatch shale/siltstone; and a composite of the Wasatch units in the deepest layer of the model (Deep Wasatch). Initial hydraulic conductivity values for each zone (**Table 10**) were assigned based on a combination of literature values and results from aquifer tests conducted in the PAPA (see Section 2.4). These values were refined during the calibration process, and zones were added to account for heterogeneity (see Section 4.0). The hydraulic conductivity of the Wasatch Formation likely varies over several orders of magnitude owing to variability in local lithology (e.g., coarse-grained sandstone versus fine-grained shale/siltstone). Hydraulic conductivity values from 270 independent estimates in the Wasatch Formation ranged from 0 foot/day to 2,106 feet/day (Clarey et al., 2010).

4.0 MODEL CALIBRATION

The model was calibrated to hydraulic head values measured in the field, field-measured flow in the New Fork River, and estimated groundwater flux rates. The following subsections describe the process used to calibrate the flow model to steady-state conditions and discuss parameterization of the final calibrated model.

4.1 Steady-State Calibration

The model was calibrated to steady-state conditions. A set of 97 hydraulic head target wells were selected after reviewing groundwater elevations measured in 108 wells within the model domain (AMEC, 2012). Head targets used for model calibration are listed in **Appendix C**. Water levels measured in 11 of the 108 wells were anomalous (i.e., a difference of greater than 30 feet versus water levels measured in nearby wells) and were therefore not used as targets. The following table presents a breakdown of when target elevations were measured:

Measurement Date	Number of Target Wells
2009	27
2010	69
2011	1
Total	**97**

Most target head values were selected from the 2010 set of water level measurements because it is the most comprehensive. The 27 targets from 2009 did not have water level measurements after 2009, but the additional targets improve the spatial coverage of groundwater levels within the model domain. One water level measurement[1] from 2011 was used, because the 2010 water level measured in that well was anomalously high (50 feet above groundwater elevations in nearby wells), but appeared to have returned to a representative level at the time of the 2011 measurements.

Target values for wells that are screened across multiple layers were placed in the layer corresponding to the mid-point of the well screen (see **Section 4.3**).

The table below summarizes the number of targets in each layer of the model:

Layer	Number of Head Targets	Layer	Number of Head Targets	Layer	Number of Head Targets	Layer	Number of Head Targets
17	4	35	1	49	4	60	1
21	3	36	1	50	2	61	1
22	1	37	4	52	3	62	3
23	2	39	1	53	2	65	2
26	1	41	8	54	4	67	3

1. Study well T-3-SW was drilled using a guar gum drilling fluid. Following well installation and initial water level measurement in 2010, the water level declined approximately 50 feet over several months. The measurement collected on June 9, 2011, is believed to be representative of static conditions as it was collected after significant additional well development (AMEC, 2012).

Layer	Number of Head Targets	Layer	Number of Head Targets	Layer	Number of Head Targets	Layer	Number of Head Targets
27	2	42	3	55	5	Note: There are no head targets in layers that are not listed	
28	1	43	6	56	1		
29	7	44	2	57	3		
31	2	45	3	58	2		
33	1	47	6	59	2		

All head targets are from wells that have had their location (position and elevation) established by survey; therefore, given the survey method (AMEC, 2009b), elevation measurements are estimated to be accurate to within ±0.2 foot. The majority of water levels (65 out of 97) were measured with a sonic water level meter and corrected based on a rating curve developed between the electric tape and sonic water level meter (**Appendix D**). The remaining 32 wells were measured with an electric tape. Electric tape measurement error is a few hundredths of a foot. However, sonic water level meters require settings that account for both the average daily air temperature and the well water temperature. Furthermore, gases other than air (e.g., methane) in the well bore can lead to additional measurement error. The error associated with the sonic water level meter is likely about 2 to 3 feet. **Figure 1** of **Appendix D** shows the rating curve and equation used to correlate sonic and electronic tape water level measurements. Seasonal fluctuation in groundwater elevation is generally within 2 feet based on a review of continuous data collected in several wells between November 2010 and June 2011. These relatively small changes in groundwater elevations have minimal effect on interpreted horizontal groundwater gradients and interpolated flow directions; however, seasonal fluctuations do have an effect on vertical groundwater gradients (see **Section 2.3.2.1**; **Figures 6** and **7**). These errors are additive; thus head targets are likely accurate to within ±5 feet. Based on this information, a calibration goal of ±10 feet was established as an acceptable residual.

In addition to head targets, six vertical gradient targets from paired study wells (AMEC, 2012) were used for model calibration (**Appendix C**). Vertical gradient targets, for wells that are within 50 feet of each other but are screened at different depths, are calculated as the difference between groundwater elevations divided by the distance between the midpoints of the well screens. **Figures 6** and **7** present the location and magnitude of vertical gradients. Wells with artesian flow were not used as vertical gradient or head targets because the head values were estimated. In addition, study well pairs T-7 and T-1 were not used as vertical gradient targets because water levels in the shallow wells were considered anomalous. The calibration goal for vertical gradient targets is ±0.05 feet/foot.

Flux targets for base flow are based on estimates developed for the groundwater balance (see **Section 2.5**). Flux targets representing flow between groundwater and surface water for all major streams in the model domain are based on field-measured data (**Table 11**). Flux targets for the New Fork River are based on results of synoptic stream gauging conducted in November 2009. Other stream flux targets are based on USGS data and/or data collected by AMEC. If available, USGS data from November 2009 were used to calculate flux. When data for November 2009 were not available, the average flow for the month of November was used for flux calculations.

Calculations of flux between groundwater and the New Fork River is estimated to be accurate to within ±25 percent. Error associated with flux targets for all other streams are estimated to be at least ±100 percent, because they are based on calculations comparing measurements of flow rates at stations that were often not collected during the same year.

4.2 Calibration Process

Model calibration involves finding a realistic and supportable combination of boundary conditions, parameters, and stresses that generate head values throughout the model domain that match observed head values within a reasonable range, while simultaneously reproducing flux estimates that match measured and/or estimated values within a reasonable range. Calibration was completed according to guidelines set forth in ASTM Standard D 5981-96 (2002) and was accomplished by iteratively adjusting hydraulic conductivity and boundary conditions. Recharge was assumed to be relatively well known based on work by Martin (1996) and Hammerlick and Arneson (1998) and was not adjusted during calibration.

An iterative approach to calibration was used that included both manual and automated techniques (including parameter estimation using parameter estimation (PEST) software [Doherty, 2005]). Manual calibration involved adjustments to several parameters, including distribution and values of horizontal and vertical hydraulic conductivity; and River Package conductance. Initially, six hydraulic conductivity zone values were incorporated into the model representing the following geologic units: Mesa Terrace gravel deposits; glacial outwash; alluvial deposits; Wasatch sandstone; Wasatch shale/siltstone; and a composite of the Wasatch units in the deepest layer of the model (Deep Wasatch) (see **Section 3.2.3**; **Table 10**).

PEST is model-independent parameter optimization software that is commonly used in groundwater flow modeling to automate the calibration process. PEST is run on an existing model and uses specified parameters to minimize an objective function. In this case, PEST used horizontal hydraulic conductivity (parameter) to minimize the sum of squares (objective function) for head targets in the model (**Appendix C**). A range of values for the different hydraulic conductivity zones was defined using field-measured hydraulic conductivity estimates and literature values. During each PEST run, the horizontal hydraulic conductivity zone values were changed within the specified range using a different combination of values. Once the sum of squares was minimized, PEST stopped running and the model was updated with the new combination of hydraulic conductivity values.

Figure 16 illustrates the progress of calibration in statistical terms based on head residuals and target flux residuals. **Appendix E** lists the parameters used during calibration, ranges of values for each parameter, the rationale for each range, and the final calibrated value/range for each parameter (Fetter, 2001; Domenico and Schwartz, 1990). **Appendix F** lists adjustments made to the model iteratively during the calibration process, including refinement of hydraulic conductivity zones and corresponding changes to calibration statistics. The calibration process can be summarized by the following steps:

- An initial PEST run was executed using the six initial hydraulic conductivity zones assigned in the model; this PEST run produced residual statistics that did not meet calibration criteria.
- Next, manual calibration was completed that included adjusting hydraulic conductivity values and increasing the number of hydraulic conductivity zones to 17. Hydraulic conductivity zones were added in areas where the regional potentiometric surface map (**Figure 7**) indicated a change in the hydraulic gradient and were not based on lithologic data. These changes in hydraulic gradient are interpreted to represent changes in hydraulic conductivity. Areas with lower hydraulic gradients were assigned relatively higher hydraulic conductivity values (and vice versa). These adjustments allowed the model to more effectively represent heterogeneities present within the various lithologic units represented in the model.

- Hydraulic conductivity values from the manual calibration were then optimized using PEST. The PEST run produced calibration statistics within the calibration goal for head targets but did not produce acceptable results for flux targets.
- Additional manual calibration followed PEST optimization. Additional manual calibration steps included increasing the number of hydraulic conductivity zones to 23 and adjusting several hydraulic conductivity and streambed conductance values.
- Finally, a round of automated calibration was executed leading to the calibrated model. The final automated calibration included increasing and decreasing horizontal and vertical conductivities one zone at a time by an order of magnitude. In some cases, changing conductivity values by an order of magnitude resulted in hydraulic conductivity values outside of the reasonable range established using aquifer test results and literature values. When this occurred, the calibration values were changed to the minimum or maximum reasonable conductivity value based on the lithologic type. After the model was run using the changed value, model statistics were recalculated. If the change in hydraulic conductivity for a zone resulted in improved model statistics, the change was incorporated into the model; otherwise, the previous value was used.

4.3 Evaluation of Steady-State Calibration

Both qualitative and quantitative methods were used to judge calibration results. Simulated potentiometric surface maps were compared to those interpolated from field-measured heads and judged qualitatively based on visual comparison of fit. **Figure 17** shows the simulated potentiometric surface map; comparison of the simulated (**Figure 17**) and interpolated (**Figure 7**) potentiometric surfaces indicate a good match between groundwater elevations and gradients.

Calibration statistics were evaluated for both single-layer well targets and multi-layer targets for wells screened across multiple layers (**Figure 18)**. **Figure 18A** presents a plot showing observed versus simulated heads. The values appear randomly distributed on either side of the regression line, suggesting that the model is well calibrated and not biased toward heads that are too high or too low. **Figure 18B** shows the statistical distribution of residuals, showing that the error is generally distributed in a normal fashion. **Figure 18C** shows the relationship between residuals and observed head. The plot indicates that the errors are generally evenly distributed for all head elevations, exception for low head values (between 6,800 and 6,825 feet) in Layer 41, where the errors are all around +5 feet. **Figure 18D** shows the relationship between residuals and layer thickness. All four plots in **Figure 18** indicate the model is well calibrated.

Table 12 presents statistics for residuals calculated for both the single-layer and multi-layer targets. All single-layer target residuals fall within the established calibration goal of ±10 feet (**Table 12**). The calculated mean residual is 0.16, with a standard deviation of 4.53. A mean residual close to zero indicates the model is not biased toward heads that are too high or too low. The absolute mean residual is 3.77, and the scaled standard deviation is 1.2 percent. According to Anderson and Woessner (1992), in a well-calibrated model, the residual standard deviation should be a small portion (less than 10 percent) of the total change in head across the model domain (scaled standard deviation). These calibration statistics suggest the model is well calibrated to observed values of hydraulic head.

As noted earlier, for target wells screened across multiple layers, a simplifying assumption was made that the head simulated in the model layer representing the mid-point of the screen is characteristic of the head observed in the well bore (see **Section 4.1**). To evaluate the effect of this simplifying assumption on the quality of calibration, single-layer targets were replaced with head values from wells estimated using the FWL4 Package (**Table 12**). The FWL4 Package calculates the head value in a well based on properties assigned to each layer the well is screened across, and on the properties of the well bore. Single-layer targets were replaced with FWL4 Package wells that have a pumping rate of zero. The model was then rerun, and calibration statistics for the resulting model were recalculated using the simulated head in the FWL4 wells (**Table 12)**. Calibration statistics based on FWL4 wells are similar to those calculated based on single-layer targets, suggesting the calibration is not sensitive to this simplifying assumption.

In some cases, transient effects related to long-term temporal changes in groundwater elevations can affect the quality of a steady-state calibration. In order to assess the potential effects of such temporal variability on model calibration, residual statistics were calculated separately for targets based on measurements taken in 2009. These statistics were then compared to overall calibration statistics using all targets. **Figure 19** presents observed vs. simulated head values for targets based on measurements in 2009. Values appear to be randomly distributed on either side of the regression line, indicating the model is not statistically biased to 2009 target values. **Table 13** compares calibration statistics of residuals for all targets to those based on only 2009 targets. Calibration statistics for the 2009 targets are similar to those for all targets. The residual mean for the 2009 targets was negative, indicating that the 2009 groundwater elevation measurements are slightly over-predicted in the model compared to the measurements from 2010 and 2011.

Figure 20 presents a map of positive and negative residuals across the model domain, and **Appendix G** presents residuals for each layer and hydraulic conductivity zones. Positive (blue) residuals plotted on **Figure 20** indicate the simulated head is below the observed target value, and negative (red) residuals indicate the simulated head is higher than the observed target value. The apparent random distribution of positive and negative residuals indicates the model does not exhibit spatial bias (i.e., over- or under-predict head in any portion of the flow system where observed data exist).

Table 14 presents simulated and measured differences in water levels and the residual for each vertical gradient target. All vertical gradient targets were within the calibration goal of ±0.05 feet/foot. This finding suggests that the model is capable of reproducing vertical flow in the PAPA groundwater system.

In addition to calibrating to observed heads, the model was calibrated to estimated fluxes. **Table 15** presents the simulated and estimated groundwater balance. All simulated groundwater balance fluxes are within the margin of error of ±25 percent of the estimated value and/or within the calculated range of values, except for fluxes associated with well pumping.

Table 16 presents simulated and measured or estimated base flow for streams and rivers in the model. Simulated base flow for the New Fork River is 26 percent lower than the estimated flow. Base flow to all other streams except Boulder Creek is within an order of magnitude. A difference of an order of magnitude is appreciable; however, given the assumed error in calculated base flow, order of magnitude variability is acceptable for the model calibration. The data available for Boulder Creek (AMEC [2012] measurement at the mouth in November 2009 and historic [1938-1972] average November flow below Boulder Dam) suggest the stream is losing water. Since the flow data for the upgradient and downgradient stations are

from different periods, the reliability of the target flux of -6.1 feet^3/second is doubtful, especially since all other streams along the eastern boundary of the model appear to be gaining flow.

4.4 Calibrated Model Parameters

Table 17 presents the horizontal hydraulic conductivity (*K*h) and vertical hydraulic conductivity (*K*v) values simulated for each hydrogeologic zone. Figures in **Appendix G** present the calibrated horizontal hydraulic conductivity values and distribution for Layers 2 through 69; Layer 1 is inactive and therefore is not included in **Appendix G**. **Figure 21** presents a cross-section of calibrated vertical hydraulic conductivity zones. Horizontal hydraulic conductivity for Wasatch sandstone units ranged from 1.0 foot/day to 30 feet/day, and vertical hydraulic conductivity ranged from 0.01 foot/day to 4 feet/day. Wasatch shale/siltstone horizontal hydraulic conductivity ranged from 0.005 foot/day to 6 feet/day, and vertical hydraulic conductivity ranged from 0.0005 foot/day to 0.24 foot/day. Alluvial deposits were simulated using a horizontal hydraulic conductivity ranging between 6 feet/day and 400 feet/day and a vertical hydraulic conductivity ranging between 1 foot/day and 4 feet/day. The deep Wasatch (Layer 69) was simulated as a mixture of sandstone and shale/siltstone units; horizontal hydraulic conductivity ranged between 0.043 foot/day and 18 feet/day, and vertical hydraulic conductivity ranged between 0.01 foot/day and 4 feet/day. Distribution of different hydrogeologic zones in Layer 69 was not based on lithology but rather on changes in the observed hydraulic gradient (**Figure 7**) and resulting calibration statistics. Mesa terrace gravel deposits were simulated with a horizontal and vertical hydraulic conductivity of 100 feet/day. Glacial outwash, located along the slopes of the Wind River Range, was simulated with a horizontal and vertical hydraulic conductivity of 60 feet/day.

Table 18 presents calibrated parameter values for the streams and rivers. Boundary width for River Package cells ranged between 1 foot and 160 feet, and depth ranged between 1 foot and 5 feet. Simulated hydraulic conductivity of streambed material ranged between 0.1 foot/day and 100 feet/day.

4.5 Calibration Summary

A well-calibrated model must be able to reproduce field-measured data within predefined calibration criteria. The model described above was calibrated to field-measured groundwater elevations and flow in the New Fork River, and estimated groundwater flux rates. The model calibration was then evaluated both qualitatively and quantitatively using these data. The calculated mean residual was 0.16, with a standard deviation of 4.53 (**Table 12**). A mean residual close to zero indicates the model is not biased toward heads that are too high or too low. The absolute mean residual was 3.77, and the scaled standard deviation is 1.2 percent. According to Anderson and Woessner (1992), in a well-calibrated model, the residual standard deviation should be a small portion (less than 10 percent) of the total change in head across the model domain (scaled standard deviation).

Qualitative evaluation of the model was conducted by visually comparing hand-drawn potentiometric surfaces (**Figures 6** and **7**) to the simulated potentiometric surface (**Figure 17**). The comparison shows a good fit between interpolated and simulated potentiometric surfaces. Although the model does not reproduce field-measured data exactly, all target residuals are within pre-defined calibration criteria; thus, the model can be considered well calibrated to current groundwater conditions within the PAPA.

5.0 SENSITIVITY ANALYSIS

A degree of uncertainty is inherent to any modeling effort. The purpose of sensitivity analysis is to quantify the uncertainty in model simulations caused by estimates of model parameters (Anderson and Woessner, 1992). During sensitivity analysis, model input parameters are systematically changed one at a time within reasonable ranges to determine the effect on model calibration of changing model input parameters. Parameters can be considered sensitive or insensitive parameters. For a *sensitive parameter,* a small change causes a relatively large change in the model outcome, whereas for an *insensitive parameter*, even large changes in the input parameter cause relatively little change in the model outcome.

A sensitivity analysis was performed on the calibrated steady-state model by systematically adjusting horizontal and vertical hydraulic conductivity, total recharge, and the PET rate and extinction depth. The absolute residual mean from the calibrated model was used as a measure of the sensitivity of the model to each parameter.

5.1 Hydraulic Conductivity

The hydraulic conductivity sensitivity analysis included adjustment of the horizontal and vertical hydraulic conductivity for each zone (**Figure 21** and **Appendix G**) upward and downward by one order of magnitude (i.e., the calibrated value was multiplied by 0.1 and 10 and the results were used to run the model). In addition to adjusting each zone by one order of magnitude, adjustment of the three dominant hydraulic conductivity zones (Zones 1, 2, and 4) was performed using eight different multipliers (0.1, 0.25,

0.5, 0.75, 2.5, 5, 7.5, and 10). Hydraulic conductivity Zones 1 and 2 represent the majority of sandstone and shale/siltstone, respectively, in the model domain, and Zone 4 represents the bottom layer of the model, a mix between shale/siltstone and sandstone.

Figure 22 presents the results of the horizontal hydraulic conductivity sensitivity analysis. The model is more sensitive to increases in horizontal hydraulic conductivity than decreases. Zones 1, 4, 5, 8, 9, and 14 are the most sensitive, while the remaining zones are slightly sensitive or not sensitive. Zone 1 and Zone 2 are significantly more sensitive to increases in horizontal hydraulic conductivity than to decreases, and Zone 4 is slightly more sensitive to decreases than to increases.

Figure 23 presents the results of the vertical hydraulic conductivity sensitivity analysis. The model is most sensitive to decreases in vertical hydraulic conductivity in Zones 2 and 4. In fact, based on absolute mean of residuals, the model shows the highest sensitivity to decreases in vertical hydraulic conductivity in Zone 2 among all the sensitivity simulations analyzed. Otherwise, the model is not sensitive to changes in vertical hydraulic conductivity.

5.2 Total Recharge

Total recharge includes both natural recharge and irrigation recharge and was simulated in the calibrated model using a value of 20,102 acre-feet/year. For the sensitivity analysis, total recharge was varied from a minimum of 10,051 acre-feet/year to a maximum of 30,153 acre-feet/year using 10 different multipliers. Minimum and maximum values were chosen in order to cover the range of values calculated for the groundwater balance (13,450 – 19,890 acre-feet/year), which were based on work by Martin (1996) and Hammerlick and Arneson (1998). **Figure 24** presents absolute residual mean for the total recharge

sensitivity analysis. The results show that the model is sensitive to recharge, and slightly more sensitive to increases in total recharge than to decreases.

In addition, total recharge was set equal to zero in the model domain in order to assess how this parameter potentially affects groundwater flow paths and travel times (see **Section 6.1.3**). Setting recharge equal to zero resulted in an absolute residual mean of 6.47 feet and flux targets for the streams that were not within the reasonable range estimated for the groundwater balance (see **Section 2.5**). This sensitivity analysis is discussed further in **Section 6.1.3**.

5.3 Evapotranspiration

The PET rate and extinction depth were adjusted using 10 different multipliers. The PET rate was changed to values ranging from 8.75 inches/year to 26.25 inches/year, and the extinction depth was changed to values ranging from 2.5 feet to 7.5 feet. The range of values for PET rate was chosen such that it covered the range used for the groundwater balance (15 – 20 inches/year). The range for extinction depth was chosen based on variation in vegetation and soil materials and estimates from Shah et al. (2007). **Figure 25** presents the results of the sensitivity analysis for the ET parameters. The model is not sensitive to reasonable changes in the PET rate or in the extinction depth. This insensitivity likely arises because ET is a small component of the flow budget and is applied only in the riparian zones of the model (**Figure 15**), whereas the calibration targets are located mainly where ET is not applied (**Figure 20**).

5.4 Summary of Sensitivity Analysis

A sensitivity analysis was performed on the calibrated steady-state model by systematically adjusting horizontal and vertical hydraulic conductivity, total recharge, and the PET rate and extinction depth. The absolute residual mean from the calibrated model was used as a measure of the sensitivity of the model to each parameter. Results of the sensitivity analysis show that PET rate and extinction depth are the least sensitive among the parameters selected for sensitivity analysis, and hydraulic conductivity and total recharge are the most sensitive. **Tables 19** and **20** summarize input values used during the sensitivity analysis, and **Appendix H** presents absolute residual mean for each model run.

6.0 TRANSPORT MODELING

AMEC performed advective transport modeling for receptors and sources, and solute transport modeling for five hypothetical scenarios. The following sections describe parameterization and results for transport modeling.

6.1 Advective Transport

Advective transport modeling by particle tracking is routinely used to help visualize groundwater flow fields and track actual or hypothetical contaminant paths in an aquifer. *Advective transport* is the movement of a solute at the speed of the average linear velocity of groundwater. Particle tracking involves tracing the movement of infinitely small imaginary particles in a groundwater flow field based on groundwater velocities and direction. Particles are given a starting location and traced for a defined time period. The movement of each particle produces a *path line*, a general term used to refer to a groundwater flow path (Anderson and Woessner, 1992).

MODPATH (Pollock, 1994) is a three-dimensional particle tracking code that uses groundwater velocity vector fields generated from MODFLOW head output to simulate advective transport in a groundwater system. Advective transport modeling by particle tracking does not take into account the effects of dispersion, adsorption, or biodegradation, and assumes that dissolved contaminants move at the same velocity as groundwater.

There are two types of particle tracking, reverse and forward. In reverse particle tracking, particles are placed in a flow field and tracked backward (opposite direction of groundwater flow) along path lines to a source. Reverse particle tracking is used to determine sources of groundwater or contamination. For example, particles may be placed in a flow field at the location of a screened interval for a well and the model run using reverse particle tracking. The resulting path lines indicate the source of groundwater for the well. In forward particle tracking, particles are placed in a flow field and tracked forward in the direction of groundwater flow. Forward particle tracking is useful for predicting the direction of groundwater flow or contamination movement. For example, if a spill were to occur at a given location, the hypothetical particles could be placed in a flow field around the source and the model run using forward particle tracking. The resulting path lines would show the likely path of contaminant transport.

For this study, particle tracking was used to (1) identify areas in the PAPA that are potentially susceptible to contamination from natural gas activities; (2) assess the susceptibility of wells in and around Pinedale related to a potential, hypothetical release due to natural gas activities; and (3) identify specific receptors in the PAPA that may be impacted by a hypothetical release due to natural gas activities if contamination were to occur.

6.1.1 Methods

In cooperation with the Operators and BDE during meetings conducted between May and August 2011, AMEC identified potential sources of groundwater contamination associated with natural gas operations and potential receptors of concern in and around the PAPA (**Table 21**). Forward and reverse particle tracking methods were used to evaluate flow paths and travel times from potential sources to potential receptors.

The first step involved reverse particle tracking performed on potential receptors of concern. Reverse particle tracking was performed to identify areas contributing groundwater to potential receptors. Hypothetical particles released in and around potential receptors were simulated and the model was run in reverse for periods of 10 years and 110 years (which is two times the expected life of the Pinedale Anticline natural gas field [BLM, 2008a]). The potential receptors identified for use in the reverse particle tracking simulation included domestic wells located in river corridors, stock wells, the New Fork River, the Green River, and irrigation ditches (**Table 21**). Domestic and stock wells were identified using the WSEO (2010) well database. For the receptor wells, particles were placed within the model in a ring around each well in every model layer in which the well is perforated. Particles were placed in each River Package cell representing the New Fork River, Green River, and irrigation ditches. In several areas, the elevation of irrigation ditches and stock wells are above the simulated regional potentiometric surface, which resulted in no particle movement. These stock wells are not dry but rather intercept perched groundwater above the regional groundwater system that was not simulated in the model. For each well and irrigation ditch, two vertical release points were used in each cell, resulting in two particles for each starting location; for rivers, three vertical release points were used per cell, resulting in three particles for each starting location. Using multiple vertical release points in a cell provides a more accurate depiction of all the areas contributing groundwater to a receptor based on results of the flow model.

Following the reverse particle tracking, forward particle tracking was performed to simulate hypothetical releases, flow paths, and travel times from six types of potential sources: shut-in pre-1984 natural gas wells (natural gas well that is not currently producing; it was conservatively assumed that all pre-1984 natural gas wells are shut-in and not plugged and abandoned), liquid-gathering facilities, natural gas pads, pipelines, roads, and saltwater disposal facilities (**Table 21**). Results from the reverse particle tracking were used to define the zone within the PAPA that encompasses all 110-year flow path lines that lead to potential receptors (see also **Section 6.1.2**). Forward particle tracking was then performed from natural gas pads and roads within the zone encompassing all 110-year reverse particle tracks in order to reduce repetitive simulations and to allow for better visual evaluation of results. Forward particle tracking from pipelines was simulated only within 5 miles of rivers, based on discussions between the Operators and BDE. Particles for shut-in pre-1984 natural gas wells were placed in a ring around each well starting at the simulated water table and then in every third layer vertically along the entire length of the well casing within the model domain. Particle tracking from liquid-gathering facilities, natural gas pads, and saltwater disposal facilities was simulated by placing a ring of particles at the water table directly beneath the source. Particle tracking from pipelines and roads was simulated by placing a line of particles along each road and pipeline. One vertical release point was used to simulate all forward particle track scenarios.

In addition to particle tracking from sources and receptors, forward and reverse particle tacking was performed on 15 industrial water supply wells located throughout the PAPA that were selected based on BDE, Operator, and AMEC meetings between July and August 2011 (**Table 22**). These simulations were conducted at the request of BDE because hydrocarbons were first detected in the PAPA in samples from industrial water supply wells. Reverse particle tracking was performed from the midpoint of the screened interval to represent a potential receptor. Forward particle tracking was performed along the entire length of the well to simulate a failure along the casing representing a potential source. Particles were placed in a ring around each well starting at the water table and then in every third layer to the bottom of the well casing. One vertical release point was used for particle tracks in all industrial water supply wells.

Advective transport modeling requires that the effective porosity (i.e., the percentage of interconnected rock that can transmit water) be defined for each lithologic material represented in the model. Because effective porosity values have not been measured in the field, literature values were relied upon for the modeling effort. **Table 23** presents effective porosity values, calculated by Yu et al. (1993) using total porosity and field capacity, for lithologic materials applied to the model.

6.1.2 Results

Figures 26 through **29** present results for reverse particle tracking from domestic wells, the New Fork and Green rivers, stock wells, and irrigation ditches, respectively. Results from reverse particle tracking were used to delineate the area that encompasses all 110-year path lines within the PAPA (**Figure 30**) (including those generated by the most conservative uncertainty analysis; **Section 6.1.3**). The zones shaded green on **Figure 30** show the portion of this area that does not contain identified potential sources related to natural gas activity; this area includes the Town of Pinedale and all of the Green River corridor within the model domain. The zone shaded blue is the portion of this area where potential sources exist (**Figure 30**).

Reverse particle tracking produced the following key findings:

- In general, 110-year path lengths are less than 1.5 miles for groundwater in the Wasatch Formation. Particles moving at the average linear groundwater velocity in the Wasatch Formation would take 9 years to travel the typical width of an individual natural gas well pad (650 feet).
- Transport velocities in alluvial material along the New Fork and Green rivers are 100 to 700 times greater than those in the Wasatch Formation.
- Because the source of groundwater for wells in and around Pinedale is north of town near Fremont Lake as indicated by reverse particle tracking, these wells are not vulnerable to potential releases from natural gas exploration and production activities in the PAPA (**Figure 26**).

Results of forward particle tracking for shut-in gas wells, liquid-gathering facilities, natural gas pads, pipelines, roads, and saltwater disposal facilities are presented in **Figures 31** through **36**, respectively**.** Particles released in alluvial deposits near the New Fork River south of the Mesa or Sand Springs Draw reach receptors within 110 years, and generally in less than 10 years. Most particles released outside of the river corridors in the Wasatch Formation travel less than 1.0 mile in 110 years. **Figures 31** through **36** illustrate the following findings:

- Particles from the four shut-in pre-1984 natural gas wells closest to the New Fork River reach the river within 110 years (**Figure 31**), whereas particles from the other shut-in pre-1984 wells do not reach any other receptors.
- None of the particles released from the 10 liquid-gathering facilities within the PAPA reach an identified receptor within 110 years (**Figure 32**).
- All of the particles from natural gas pads that reached receptors were released from pads located in or near alluvial material near the New Fork River and Sand Springs Draw (**Figure**

33). Approximately 30 percent of particles released from natural gas pads reached an identified potential receptor.

- Of the particles released from pipelines or roads, only particles originating from locations in or near alluvial material along the New Fork River and Sand Springs Draw reach an identified potential receptor within 110 years (**Figures 34** and **35**).
- Particle tracks from 3 of the 12 saltwater disposal facilities reach identified potential receptors. These three facilities are located near the New Fork River, south of the Mesa (**Figure 36**).

Reverse and forward particle tracks for industrial water supply wells are presented in **Figures 37** and **38,** respectively. Particle tracking results from industrial water supply wells are similar to those for other sources and receptors in that path lengths for particles released in the Wasatch Formation are much shorter than path lengths for particles released in alluvial deposits. Forward particle tracking showed particles from two industrial water supply wells, both of which are located in or near alluvial material, reach the New Fork River within 110 years (**Figure 38**).

6.1.3 Uncertainty Analysis

Similar to sensitivity analysis (see **Section 5.0**), uncertainty analysis attempts to quantify how selected model parameters influence the uncertainty of model predictions. An uncertainty analysis was performed to estimate the degree of uncertainty in predictions that could result from estimates of hydraulic conductivity (**Figures 39** through **42**), effective porosity (**Figures 43** through **46**) and total recharge (**Figure 47**). To assess uncertainty, hydraulic conductivity of the entire model domain was both increased and decreased using multipliers of 0.5 and 5 (**Table 24**), and the flow model and reverse particle tracking were executed using the revised parameter estimates. Effective porosities for the different lithologic materials were increased and decreased to the minimum and maximum values presented in **Table 23**. Total recharge was set equal to zero for the entire model domain. The model was executed to assess the effects of changes in these parameters on predictions of path length for particles.

Increasing the hydraulic conductivity (**Figures 39** through **42**) and decreasing the effective porosity (**Figures 43** through **46**) resulted in increased flow path lengths. Decreasing the hydraulic conductivity and increasing the effective porosity resulted in decreased flow paths. The largest increase in flow path length occurred when hydraulic conductivity was increased, and the largest decrease in flow path length occurred when effective porosity was increased. Decreasing hydraulic conductivity resulted in an average decrease in path length of 29 percent, and increasing hydraulic conductivity increased path lengths by an average of 129 percent. Decreasing effective porosity resulted in an average increased path length of 46 percent, and increasing effective porosity decreased average path length by 17 percent.

In addition, as discussed in **Section 5.2**, total recharge was set to zero to assess the effect on model results. Forward particle tracks from natural gas pads within the zone encompassing all 110-year reverse particle tracks were simulated to determine if a change in recharge affects travel times and flow directions. **Figure 47** presents the results of this run. When compared to **Figure 33**, there is little change in either flow direction or travel time, with two exceptions discussed below, indicating that a change in recharge has little effect on advective transport in the PAPA. Two areas were sensitive to a decrease in recharge: the center of the PAPA north of the New Fork River and the western edge of the zone encompassing all 110-year reverse particle tracks north of the New Fork River. Path lengths in these two areas were reduced when recharge was removed from the model.

6.2 Solute Transport

Solute transport modeling simulates the conveyance of dissolved chemicals in groundwater. Unlike advective transport modeling, solute transport modeling takes into account mechanical dispersion, adsorption, and biodegradation. Whereas advective transport modeling considers only groundwater velocity, solute transport modeling simulates dissolved solute interaction with aquifer materials that may increase or decrease the velocity of solutes in the groundwater system.

Solute transport modeling was used to assess fate and transport of certain hydrocarbon compounds and chloride that could potentially result from hypothetical releases. The solute transport modeling included:

simulating the maximum lateral and vertical extent of detectable hydrocarbon and chloride concentrations in groundwater from hypothetical releases; (2) determining maximum solute concentrations expected in groundwater due to hypothetical releases; and, (3) simulating the expected duration of detectable concentrations of hydrocarbons and chloride in groundwater following hypothetical releases.

MODFLOW-SURFACT was used to assess hypothetical scenarios representing a solute released into the groundwater system related to natural gas operations in the PAPA. MODFLOW-SURFACT's transport module is capable of simulating advective-dispersive transport, linear and nonlinear retardation, and first-order decay and biochemical degradation in soil and/or water. In addition, MODFLOW-SURFACT is capable of simulating multi-phase transport and variable density water. Multi-phase transport was not simulated, as it was not an objective of this project. Movement of water through the unsaturated zone to the water table is simulated using MODFLOW-SURFACT's pseudo-soil function. The pseudo-soil function is a simplified unsaturated flow model based on Gravity-Segregated-Vertical-Equilibrium conditions (Huyakorn et al., 1994). No data are available for the unsaturated zone in the model beyond driller's logs. As a result, flow and transport in the model were simplified in the unsaturated zone and generalized over large areas.

The Operators, BDE, and AMEC selected five hypothetical release scenarios to simulate during meetings held between July and August 2011 (**Figure 48**). AMEC developed model inputs for each scenario based on results from conducting field investigations described by AMEC (2010), information provided by the Operators, and scientific literature. Hypothetical source areas for each scenario were selected from within the zone encompassing all of the 110-year tracks from the reverse particle tracking (the blue zone on **Figure 48**; see **Section 6.1.1**). Source area locations were selected to both maximize the spatial distribution of the hypothetical releases within the 110-year zone that encompasses potential sources and to capture variability in operational activities used in natural gas drilling and transportation. Source areas were selected from the area of highest grid refinement near the center of the PAPA. Performing solute transport simulations in smaller model cells provides better resolution for simulated concentrations and therefore a better understanding of solute transport processes.

The solute transport modeling addressed the following five hypothetical release scenarios (**Figure 48**):

1. A truck spill of condensate on Paradise Road;
2. A pipeline leak of produced water north of the New Fork River and south of the Mesa;
3. A spill of condensate due to failure of a storage tank at a liquid-gathering facility;
4. A frac tank spill on a natural gas pad; and

5. A leak from the shut-in pre-1984 natural gas well Pinedale 3.

These hypothetical scenarios are not intended to match or simulate current water quality conditions in the aquifer or simulate any known incidents that have occurred. Simulation of these hypothetical scenarios is intended to aid in decision-making regarding future groundwater quality monitoring. Conservative assumptions and calculations were made to generate source terms and inputs for solute transport modeling. In addition, it was assumed that no remediation of the spill would take place. In reality, Operators have pollution prevention and mitigation plans in place that reduce the possibility of a spill and, if a spill were to occur, spill remediation plans are in place that would reduce impacts to the environment.

6.2.1 Solute Transport Model Parameterization

Three solutes (benzene, toluene, and/or chloride) were selected for the solute transport modeling, and varied depending on the type of simulated release. Benzene and toluene were selected because (1) they are representative of petroleum hydrocarbon releases and have been detected in all liquids transported in the PAPA related to natural gas activities (AMEC, 2010); and (2) they are the most soluble hydrocarbons detected in the groundwater system. Chloride was chosen to represent brine releases. Chloride is a chemically conservative constituent (i.e., it does not degrade over time or adsorb onto aquifer materials); for this reason it is the constituent likely to be transported the farthest distance from the point of any potential release. **Appendix I** presents an expanded discussion of model parameterization, including all solute transport modeling input parameters.

6.2.2 Hypothetical Release Scenarios

This section describes the five hypothetical release scenarios selected for solute transport modeling (**Figure 48**). **Table 25** presents the hypothetical spill volumes and initial concentrations of solutes introduced into the model for each scenario. Concentrations resulting from hypothetical releases were calculated using results from conducting field investigations described by AMEC (2010) and published literature values. Release volumes were calculated using information provided by the Operators. Similar to particle tracking, solute transport simulations were run for 110 years (i.e., two times the expected life of the PAPA; BLM, 2008a).

6.2.2.1 Spill on Paradise Road

In this scenario, transport of benzene and toluene were simulated following the wreck of a 6,300-gallon (842 feet^3) tank truck transporting natural gas condensate on Paradise Road. Natural gas condensate is a low-density liquid hydrocarbon that generally occurs in association with natural gas. The location of this hypothetical release is displayed on **Figure 48**, and conceptualization is shown on **Figure 49**. The location was chosen because it is located upgradient of potential receptors, including domestic wells, Paradise Ditch, and the New Fork River.

It was assumed that once released, the condensate would spread out over the land surface covering an area measuring 10 feet by 50 feet. The condensate would then migrate vertically through the unsaturated zone to the water table (**Figure 49**). The aquifer material beneath the hypothetical spill site is simulated as alluvial deposits associated with the New Fork River, and the simulated depth to groundwater is 82 feet.

6.2.2.2 Leak of Produced Water from Pipeline

In this scenario, transport of benzene, toluene, and chloride was simulated assuming a catastrophic failure in a pipeline that releases produced water to the land surface (**Figures 48** and **50**). Produced water is naturally occurring water that exists in the natural gas reservoir that can travel up a well during gas production. The hypothetical spill location was chosen because it is upgradient of potential receptors, including domestic wells, Paradise Ditch, and the New Fork River (**Figure 48**).

It was assumed that prior to failure, the pipeline was completely full and all of the produced water (3,214 feet^3) between valve sets was released in a single day. Once the produced water is released, it would migrate vertically through the unsaturated zone to the water table (**Figure 50**). Based on the flow model, depth to water beneath the hypothetical spill site is 170 feet, and the subsurface is simulated as alternating shale/siltstone and sandstone layers.

6.2.2.3 Tank Failure at Liquid-Gathering Facility

In this scenario, transport of benzene and toluene was simulated assuming a catastrophic failure of a 420,000-gallon (56,150 feet^3) natural gas condensate tank at a liquid-gathering facility (**Figures 48** and **51**). In addition, it was assumed that the lined secondary containment surrounding the tank is completely breached, and all condensate reaches land surface. The location was chosen because the liquid-gathering facility is located along the crest of the Pinedale Anticline and is upgradient of several potential receptors, including a stock well, a domestic well, Paradise Ditch, and the New Fork River (**Figure 48**).

It was assumed that once the tank and secondary containment failed, condensate would spread out and cover the area of the liquid-gathering facility (246,095 feet^2) where the tank is located (**Figure 51**) (BLM WYGISC, 2009). Based on results from the steady-state model, depth to water beneath the spill is 63 feet and the subsurface is simulated as alternating shale/siltstone and sandstone layers.

6.2.2.4 Spill from Frac Tank at Natural Gas Pad

In this scenario, transport of benzene, toluene, and chloride was simulated assuming a catastrophic failure of a frac tank at a natural gas pad. A frac tank is a large rectangular tank that is used to hold water or flowback fluid when a well is being fractured. Flowback fluid is a mixture of fluids used during hydraulic fracturing (*frac fluid*) and produced or fresh water. The frac tank in this scenario is assumed to release 21,000 gallons (2,807 feet^3) of flowback fluid to the land surface. The simulated natural gas pad is located in Sand Springs Draw, a medium to high vulnerability area (Wyoming Water Resources Center, 1998), and is upgradient of a domestic well and the New Fork River (**Figure 48**).

It was assumed that the frac tank was completely full and all of the fluid was released in a single day. Once the fluid is released, it will migrate vertically to the water table (**Figures 48** and **52**). Depth to water obtained from the flow model is 18 feet, and the unsaturated material is simulated as alluvial deposits in Sand Springs Draw.

6.2.2.5 Leak from Shut-in Pre-1984 Natural Gas Well

In this scenario, transport of benzene, toluene, and chloride was simulated assuming there is a small leak in a production pipe in the shut-in pre-1984 natural gas well Pinedale 3. A shut-in well is one that has been temporarily capped and is not currently producing. Pinedale 3 is described as permanently

plugged and abandoned on the Wyoming Oil and Gas Conservation Commission website. However, for purposes of this report, it was assumed that the well has been shut-in (only temporarily capped), and that natural gas, produced water, and natural gas condensate can move up the well bore. For this hypothetical release scenario, natural gas, produced water, and natural gas condensate enter the aquifer through a leak in the gas production pipe inside the well. This well was chosen for the simulation because it is located along the crest of the Pinedale Anticline, upgradient of the New Fork River and a domestic well (**Figure 48**).

Based on a driller's log, the well was constructed with casing cemented to the borehole from the land surface to a depth of 400 feet. At depths below 400 feet, the well is an open borehole with a production pipe (**Figures 48** and **53**). It was assumed that the leak is constant and occurs in the production pipe just beneath the surface casing. At this depth, the aquifer is completely saturated and therefore the solutes are released directly into the groundwater system at a constant rate.

6.2.3 Solute Transport Results

Figures 54 through **61** present selected output for the hypothetical solute transport simulations. Information shown on the figures corresponds with the greatest lateral or vertical extent or the greatest concentrations observed during the simulation. In general, concentrations of benzene and toluene in groundwater beyond the source cell resulting from the hypothetical spills did not exceed the U.S. EPA maximum contaminant levels for drinking water (5 micrograms per liter [µg/L] for benzene; 1,000 micrograms per liter [µg/L] for toluene; 250 milligrams per liter [mg/L] for chloride). In addition, most simulated concentrations were below laboratory practical quantitation limits (PQLs) for benzene and toluene (1.0 µg/L for benzene; 1.0 µg/L for toluene; 1.0 mg/L for chloride [AMEC, 2010]). Simulated chloride concentrations were greater than the PQL outside of the source cell in three of the models. It is important to note that simulated concentrations shown in **Figures 54** through **61** are not actual concentrations that would be expected to be detected in groundwater but rather changes in concentration from background levels. Because no hydrocarbon background data were collected, actual concentrations expected in groundwater could not be simulated. In addition, because the size of the model cells is larger than the area covered by the hypothetical spills, the model is not capable of simulating small scale (<300 feet) heterogeneity, and thus simulated concentrations may vary from concentrations observed at a given point if a spill were to occur (see **Section 7.0**).

6.2.3.1 Spill on Paradise Road

For the road scenario, simulated concentrations greater than the PQL for benzene and toluene did not reach the water table (**Figure 54**). The maximum concentration was 296 µg/L for benzene and 346 µg/L

for toluene within the constant concentration cell. A constant concentration boundary is used to fix the concentration of a solute in a model cell. The maximum concentrations were fixed because of the type of constant concentration boundary that was used for the simulation. After the total mass was delivered to the system, constant concentration boundaries were removed (**Appendix I**) and simulated concentrations began to decrease. No simulated concentrations exceeded the PQL for benzene after 16.8 years or 2 years following removal of the constant concentration cell. Similarly, no simulated concentrations exceeded the PQL for toluene after 1.3 years, one year following removal of the constant concentration cell. The maximum vertical extent of dissolved solutes above the PQL was 64 feet for both benzene and toluene, which is above the simulated water table depth of 82 feet (**Figure 54**).

6.2.3.2 Leak of Produced Water from Pipeline

Simulated concentrations greater than the PQL for benzene and toluene did not reach the water table under the pipeline scenario (**Figure 55**). The maximum concentrations in the source cell were 5.9 µg/L for benzene, 4.1 µg/L for toluene, and 366.5 mg/L for chloride. The maximum concentration for each solute occurred in the source cell during the first day of the simulation. Concentrations for all simulated solutes began to decrease after the first day, after the constant flux/concentration boundary was removed, and no concentrations exceeded the PQL for benzene after 2 years and for toluene after 1 year. The maximum vertical extent for simulated concentrations above the PQL for benzene and toluene was 20 feet (**Figure 55**). Chloride concentrations above the PQL extend to the water table, reaching a maximum vertical extent of 241 feet after 110 years due to downward vertical groundwater gradients and a maximum lateral extent of 800 feet after 20 years (**Figure 56**). Chloride concentrations were greater than the PQL directly below the spill for the duration of the simulation.

6.2.3.3 Tank Failure at Liquid-Gathering Facility

Maximum benzene and toluene concentrations in the source cell for the liquid-gathering facility scenario were 51.1 mg/L and 59.8 mg/L, respectively. Simulated concentrations greater than the PQL for benzene and toluene did not reach the water table (**Figure 57**). Similar to the road scenario, the maximum concentrations were fixed because of the constant concentration boundary type that was used for the simulation. After the total mass was delivered to the system, constant concentration boundaries were removed (**Appendix I**), and simulated concentrations began to decrease. The maximum vertical extent of solute transport is 54 feet for both benzene and toluene (**Figure 57**). No concentrations exceeded the PQL for benzene after 21.2 years (16 years following removal of the constant concentration cells) and for toluene after 1 year.

6.2.3.4 Spill from Frac Tank at Natural Gas Pad

For the natural gas pad scenario, simulated toluene concentrations were above the PQL in the source cell after the first day of the simulation. Concentrations of benzene never exceed the PQL during the simulation (**Figure 58**). The maximum simulated concentrations were 0.5 µg/L for benzene and 1.3 µg/L for toluene. Concentrations of benzene and toluene did not exceed the PQL outside of the source cell, and no concentrations of toluene exceeded the PQL after year 1. The maximum simulated chloride concentration occurred in the source cell after 1 day and was 140.2 mg/L. Chloride reaches a maximum lateral extent of 1,220 feet driven by horizontal groundwater gradients and mechanical dispersion (**Figure 59**), and no chloride concentrations exceeded the PQL beginning in year two of the simulation. Concentrations for all simulated solutes decrease after the first day of simulation, after the constant flux/concentration boundary was removed.

6.2.3.5 Leak from Shut-in Pre-1984 Natural Gas Well

Simulated concentrations of benzene and toluene for the shut-in pre-1984 natural gas well reached a steady-state after 7 years and 1 year, respectively. Steady-state conditions for solute transport signify solute concentrations do not increase or decrease with time. Maximum concentrations for benzene and toluene were 362 µg/L and 24 µg/L, respectively. Benzene concentrations above the PQL had a maximum lateral extent of 650 feet and a maximum vertical extent of 34 feet (**Figure 60**). Toluene concentrations did not exceed the PQL outside of the source cell (**Figure 60**). Simulated chloride concentrations did not reach steady-state conditions during the model run. The maximum simulated chloride concentration after 110

years was 3,897 mg/L in the source cell. Chloride concentrations above the PQL reach the New Fork River after 58 years due to upward vertical gradients (**Figure 61**). The maximum concentration in a river boundary cell was 21.5 mg/L.

7.0 MODEL LIMITATIONS

Models are simplifications of complex systems, and in all modeling exercises, some model parameters are not well quantified due to a lack of data, which ultimately leads to uncertainty in model predictions. The primary objective of the modeling exercise described in this report was to develop a numerical tool that will support decisions regarding pollution prevention and water resources monitoring in the PAPA.

The model described in this report was calibrated to groundwater elevation targets concentrated in and around the axis of the Pinedale Anticline. The scarcity of data outside of the axis leads to increasing model uncertainty with increasing distance from the axis. Where data are missing or insufficient to characterize variability in the system, conservative assumptions were made in developing model inputs based on literature values. To quantify uncertainty in the model, a sensitivity analysis was conducted on select parameters. Results of the analysis show that PET rate and extinction depth are the least sensitive among the parameters selected for sensitivity analysis, and hydraulic conductivity and total recharge are the most sensitive.

The transport models described in **Section 6.0** have not been calibrated to existing conditions, because information regarding source terms is not available. For this reason, the predictive capabilities of the transport model have not been evaluated. In addition, conservative assumptions were used for solute transport model inputs (**Appendix I**) because field-measured data are not available.

Model cells are larger than the areas within which the hypothetical release was assumed to occur. Because of the model cell size, the model cannot simulate small-scale (<300 feet) heterogeneity in the unsaturated and saturated zones. As a result, the model is not capable of accurately simulating concentrations at a small scale (<300 feet); however, the model is appropriate for simulating large-scale (>300 feet) movement of potential releases and travel times from potential sources to potential receptors.

Limited information is available regarding the location of fractures and faults in the Wasatch Formation, and no information is available regarding hydraulic properties of fractures and faults. Fractures and faults can act as both conduits and barriers to flow and contaminant transport. For this reason, the model assumes that groundwater flows through a porous medium and that no preferential flow occurs through fractures in the Wasatch Formation. In reality, some preferential flow paths associated with geologic structure and secondary porosity likely exist; permeable fractures could affect groundwater flow directions and transport velocities.

The numerical model described above is appropriate for predicting flow and transport at an intermediate and regional scale. The model results are helpful in identifying vulnerable regions within the aquifer system (and in rivers/streams where groundwater is connected to surface water), and identifying appropriate locations for long-term groundwater quality monitoring.

8.0 CONCLUSIONS

Calibration of the PAPA numerical groundwater model demonstrates that the model is capable of reproducing hydraulic head values measured in the field and estimated fluxes within a reasonable range of error. Advective and solute transport modeling results are appropriate for supporting decisions regarding future groundwater monitoring in the PAPA. Conservative assumptions were used for all particle tracking and solute transport scenarios discussed in this report and assume no secondary containment, cleanup, or remediation of the hypothetical releases. The following observations were inferred based on results of groundwater flow and transport modeling:

- Groundwater in and around the town of Pinedale, and along the New Fork River from Pinedale to Boulder Creek, will not be affected by natural gas exploration and production activities in the PAPA.
- In general, particles following groundwater flow paths outside of the river corridors do not travel more than 1.5 miles in 110 years. Based on solute transport modeling (see below), only conservative solutes (i.e., solutes that do not adsorb to aquifer material, react chemically, or undergo biological degradation), such as chloride, would travel this distance; whereas movement of hydrocarbons in groundwater would be limited by natural attenuation. Traveling at the average linear groundwater velocity in the Wasatch Formation, it would take a particle 9 years to travel the typical width of an individual natural gas well pad (650 feet).
- Except for a few stock wells within the PAPA, identified potential receptors farther than
- 1.5 miles from the New Fork River south of the Mesa are not at risk of contamination from natural gas exploration and production activities should a significant release occur.
- The area most susceptible to groundwater quality impacts related to a significant release to groundwater from natural gas activities is the New Fork River valley between Boulder Creek and the downstream PAPA boundary. This conclusion is based on conservative assumptions and the combination of this area's proximity downgradient of potential source areas, relatively rapid groundwater travel times, and existing receptors including the New Fork River and groundwater users. Results suggest future groundwater monitoring should focus on this area; however, the identification of this area and potential receptors does not imply any probability of future impacts to water resources in this area.
- Results of five hypothetical release scenarios simulated within the area most susceptible to groundwater quality impacts described above indicate that predicted concentrations of benzene and toluene in groundwater do not exceed U.S. EPA maximum contaminant levels for drinking water at distances greater than 150 feet away from simulated sources. Since most of the potential receptors in this area are greater than 150 feet from oil and gas activities, and even if a major release to groundwater were to occur within this area, impacts related to petroleum hydrocarbons would be unlikely to reach most of these receptors.
- An individual release of petroleum hydrocarbons from natural gas exploration and production activities is unlikely to impact large portions of the Wasatch or Alluvial aquifers due to relatively low groundwater velocities, retardation, and biodegradation.

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