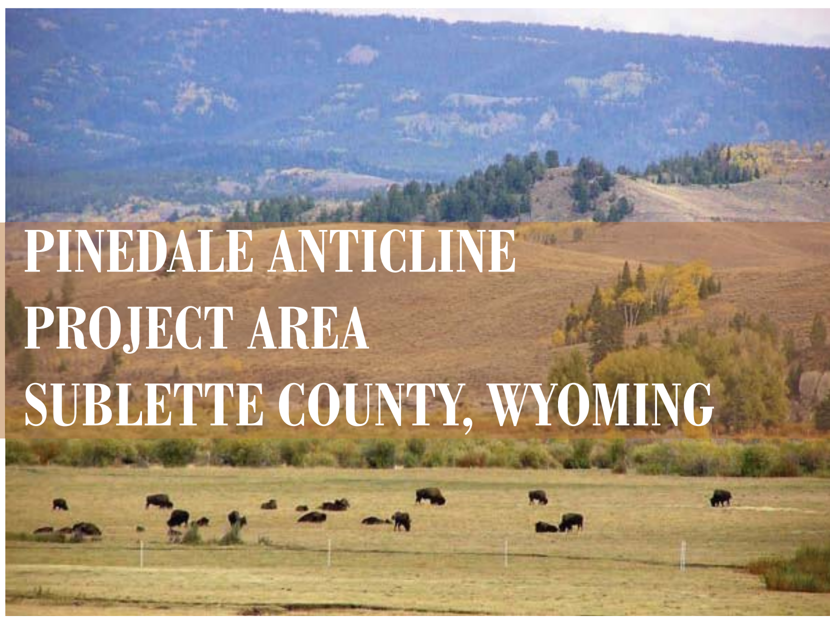
FINAL

HYDROGEOLOGIC CONCEPTUAL MODEL



PINEDALE ANTICLINE PROJECT AREA
SUBLETTE COUNTY, WYOMING

ULTRA PETROLEUM

QUESTAR Market Resources

bp America

YATES PETROLEUM CORPORATION

Geomatrix

MARCH 2008

HYDROGEOLOGIC CONCEPTUAL MODEL
Pinedale Anticline Project Area
Sublette County, Wyoming

Prepared for:

Shell Rocky Mountain Production
Ultra Petroleum Corporation
Questar Market Resources
BP America Production Company
Yates Petroleum Corporation

Prepared by:

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March 2008
Project No. 13655

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EXECUTIVE SUMMARY

Geomatrix Consultants, Inc. (Geomatrix) prepared this report to present a hydrogeologic conceptual model of the Pinedale Anticline Project Area (PAPA) as currently understood. The PAPA is a natural gas field in west-central Wyoming in Sublette County, near Pinedale, Wyoming. The work described herein was performed on behalf of the principal exploration and production companies in the PAPA including Shell Rocky Mountain Production (Shell), Ultra Petroleum Corporation (Ultra), Questar Market Resources (Questar), BP America Production Company (BP), and Yates Petroleum Corporation (Yates) (collectively referred to as the Operators). The Operators are participants in a groundwater monitoring program in the PAPA and retained Geomatrix to compile existing environmental data and develop a hydrogeologic conceptual model of the PAPA. Findings from the conceptual model were used to improve upon the current groundwater monitoring program.

STUDY AREA

Natural gas exploration and production targets natural gas accumulations in a subsurface geologic trap called the Pinedale Anticline. The uppermost gas-bearing geologic formations of economic significance are located approximately 8,000 feet below ground surface. The Anticline Crest is approximately two to three miles wide, and is oriented northwest to southeast parallel to the Wind River Range located to the east. The PAPA encompasses an area of approximately 308 square miles, and is about 12 miles wide by 26 miles long.

BACKGROUND

The USDI Bureau of Land Management (BLM) is the lead governmental agency for management of the PAPA since the vast majority of land within the production area is public land managed by BLM. The original Environmental Impact Statement (EIS) for the PAPA was issued in May 2000. In the July 2000 Record of Decision (ROD), the BLM required the Operators to implement a groundwater monitoring program in the PAPA. The Operators contracted with the Sublette County Conservation District (SCCD) to develop the groundwater monitoring program and to collect and manage groundwater data necessary to fulfill the requirements of the 2000 ROD. The SCCD began identifying water wells to be monitored in July 2001 and since 2004, has completed annual monitoring.

Since 2005, the efficacy of the groundwater monitoring program has been questioned by the agencies and Operators. In 2005 the Wyoming Department of Environmental Quality questioned the ability of the current groundwater monitoring program to detect potential impacts to groundwater resources due to uncertainties about the hydraulic connection between wells being monitored and aquifers penetrated by gas wells. In response to a proposal from the Operators for a long-term plan for exploration and development of the PAPA, BLM issued a Draft Supplemental Environmental Impact Statement (SEIS) in December 2006, and subsequently issued the Revised Draft Supplemental Environmental Impact Statement (Revised DSEIS) in December 2007. The Revised DSEIS indicates that, within six months of issuing the ROD, a new groundwater monitoring program will be developed by BLM and DEQ in accordance with the Regional Framework for Water Resources Monitoring to Energy Exploration and Development (USGS 2007a). The BLM is currently reviewing comments to the 2007 Revised DSEIS, analyzing alternatives, and anticipates issuing the final SEIS in 2008.

The Operators desire to both comply with BLM's 2000 ROD and more fully understand the groundwater system being monitored in the PAPA. The Operators retained Geomatrix to compile and analyze existing groundwater data in the PAPA with the primary objective to develop a hydrogeologic conceptual model that describes:

- Correlation between water bearing units;
- Groundwater flow;
- Interaction between groundwater and surface water;
- Variability/zonation of natural water quality; and,
- Relationships between domestic, stock, and Operator wells.

Additional objectives included identifying data gaps, reviewing the current groundwater monitoring program, and making recommendations for a revised monitoring program.

DATA SOURCES

Geomatrix researched and accessed available environmental data for the PAPA and surrounding region from a variety of sources. Key data were obtained from the SCCD and included information collected during their well survey and results of groundwater and surface water monitoring between 2001 and June 2007. Geomatrix received groundwater data from the Operators and the Wyoming State Engineer's Office, and acquired data available from the Wyoming State Climatologist Office, the US Geological Survey, and the BLM.

FINDINGS

CONCEPTUAL MODEL

Geomatrix compiled, organized, and synthesized available environmental datasets to develop a conceptual model that explains the groundwater flow system in the PAPA. The model incorporates relevant geologic, hydrogeologic, hydrologic, meteorologic and water quality data from existing sources.

Physiographic Setting

The PAPA is located in a northwest to southeast oriented valley between the Wind River and Wyoming mountain ranges. The valley is characterized by a semi-arid landscape, rocky soil, and sparse vegetation, with numerous ephemeral drainages dissecting ridges and buttes. Topographic elevations range from approximately 6850 feet where the New Fork River exits the PAPA to over 7700 feet above mean sea level on top of The Mesa in the north-central portion of the PAPA. The New Fork River and Green River are the major hydrologic features and, in the northern half of the PAPA, generally serve as the northern, eastern and western boundaries. No other significant perennial streams are located within the PAPA. Several springs occur along the slopes of topographic features within the PAPA.

Geologic Setting

Near-surface geology within and adjacent to the PAPA consists of the Tertiary-age Wasatch and Green River sedimentary formations, unconsolidated glacial outwash, and alluvium along surface water courses. The Wasatch Formation generally underlies the entire PAPA. It was deposited in a piedmont environment in an internally-drained depositional basin contemporaneous with the Green River Formation, which represents lacustrine (lake) deposition. The Wasatch Formation primarily consists of discontinuous, lenticular arkosic sandstone beds representing river channel deposits, and sandy shale and siltstone representing overbank and floodplain deposits. Due to changes in the position of the lake shoreline over time, Wasatch sediments intertongue with Green River sediments. The Green River Formation is comprised predominantly of lacustrine deposits of fine sandstone, siltstone, and shale. Beds in both of these formations are generally horizontal.

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 well logs, terrace gravels are approximately 10 to 35 feet thick. Recent alluvial deposits of unconsolidated sand, gravel, and some clay occurs in the valleys of the Green River, New Fork River and their tributaries. Alluvial deposits range in thickness up to 80 feet.

Hydrostratigraphic Units

Groundwater intercepted by industrial, stock and domestic wells occurs in three principal hydrostratigraphic units (HSUs) within the PAPA: river alluvium, Regional Wasatch Formation bedrock, and Shallow Wasatch Formation bedrock. Groundwater in the Alluvium HSU occurs adjacent to the principal water courses in the PAPA and is hydraulically connected to both rivers and streams and to the underlying Wasatch Formation. This unit is expected to have high permeability relative to bedrock HSUs.

The Regional Wasatch Formation HSU consists of laterally and vertically discontinuous porous sandstone beds interbedded with less permeable shale, siltstone, and mudstone. It is characterized as a heterogeneous or compound system as the water-bearing sandstone beds are not continuous. Because sandstone beds are lenticular and variable in location, it is not possible to correlate individual beds between boreholes based on existing well spacing in the PAPA. Due to expected hydraulic conductivity contrasts between fine-grained units and sandstone, and the discontinuous nature of the individual sandstone beds, this HSU is probably best described as a semi-confined or leaky confined aquifer. Most private wells and most industrial water supply wells that support natural gas exploration and development activities are completed in this HSU.

Groundwater in the Shallow Wasatch Formation HSU also occurs in discontinuous sandstone units or lenses within finer-grained siltstone or mudstone/shale units. Generally within the PAPA, the Shallow Wasatch Formation HSU is present above the Green River and New Fork River valleys. Based on information from driller's logs, this HSU does not appear to be continuously saturated and may be separated from the underlying Regional Wasatch HSU by unsaturated intervals at some locations. Groundwater flow in the Shallow Wasatch is primarily directed vertically downward to the Regional Wasatch Formation HSU, although some water emerges from hill slopes in the form of springs or seeps. Most stock wells are completed in the Shallow Wasatch Formation HSU.

The findings that the majority of stock wells are completed in the Shallow Wasatch Formation HSU in what appear to be discontinuous water bearing zones, and that the majority of domestic wells are completed in the Regional Wasatch Formation HSU are significant departures from previous conceptions. The 2007 Revised DSEIS (BLM 2007) states that most stock and domestic wells are completed in alluvial material.

Groundwater Recharge and Discharge

The majority of recharge occurs outside the PAPA adjacent to mountain ranges located to the northeast, north and west. Some recharge also appears to originate from the New Fork and Green Rivers in the northern portion of the PAPA. Annual recharge within the PAPA boundaries is estimated to be between 0 and 0.5 inches. The Mesa, Ross Ridge and Blue Rim, possibly due to their topographic elevations, may receive more recharge than lower elevation portions of the PAPA. Other possible sources of groundwater recharge include leakage from irrigation ditches located on the north side of the New Fork River and from excess water irrigated to crops.

Groundwater Flow

Horizontal Groundwater Flow

The overall pattern of groundwater flow within the PAPA is from northeast to southwest away from primary recharge areas adjacent to the Wind River Range. Groundwater is somewhat mounded under The Mesa, Ross Ridge and the Blue Rim due to secondary recharge in these areas, forming a groundwater ridge.

Groundwater in the Shallow Wasatch Formation HSU is expected to migrate vertically to the underlying Regional Wasatch Formation HSU, while a portion travels laterally on top of siltstone/mudstone and discharges along the slopes of topographic features in the form of springs and seeps. Groundwater in the Regional Wasatch Formation HSU flows through the aquifer in sandstone units and along joints and fractures in sandstone, mudstone, and siltstone. The heterogeneous and fractured nature of the aquifer indicates that groundwater probably flows along tortuous preferential paths from recharge areas to discharge areas.

Vertical Groundwater Flow

Upward-directed vertical gradients are present in the Regional Wasatch Formation HSU proximal to the lower New Fork River. Numerous flowing wells are located adjacent to the New Fork River between the mouth of the East Fork River and the confluence with the Green River indicating an upward vertical potential. Groundwater in the Shallow Wasatch Formation HSU migrates downward to the Regional Wasatch Formation HSU under variable degrees of saturation.

Groundwater - Surface Water Interaction

The New Fork, East Fork, and Green Rivers exert considerable influence on groundwater flow in the northern and central portions of the PAPA. Particularly in the central portion of the PAPA, groundwater from the Regional Wasatch Formation HSU discharges to the New Fork River. Groundwater exchange with rivers probably occurs through the Alluvium HSU and at areas where Wasatch Formation bedrock is exposed in the river channels. Available flow data for the New Fork River, East Fork River, and Boulder Creek indicate the New Fork River gains flow from groundwater during base flow conditions. In the southern portions of the PAPA (south of the New Fork River), groundwater flow appears to roughly parallel the New Fork and Green Rivers except in close proximity to the New Fork River, where it is directed toward the river.

Aqueous Geochemistry

Geochemical data available for the PAPA is consistent with groundwater recharge to the PAPA primarily from the north and east with groundwater movement generally to the south and west. Similarities between water in the New Fork River and shallow wells west and south of the Town of Pinedale (both calcium bicarbonate-type) may indicate the river is recharging groundwater in the northern part of the PAPA. Sodium bicarbonate soon becomes the dominant water type, increasing with depth and distance from recharge areas as ion exchange reactions remove calcium and magnesium from groundwater and replace them with sodium from formation materials. Sulfate- and chloride-rich groundwater occurs in the southern portion of the PAPA due to longer groundwater residence times and possibly contact with different mineral assemblages.

Petroleum hydrocarbon compounds, including benzene, toluene, ethylbenzene, xylenes, total petroleum hydrocarbons in the gasoline range (TPH-GRO), and total petroleum hydrocarbons in the diesel range (TPH-DRO), were detected in 73 industrial supply wells sampled between the fall of 2006 and December 2007. The following summarizes compounds detected and exceedences of groundwater quality standards:

- Benzene was detected in samples from 13 wells, with the groundwater quality standard (5 parts per billion [ppb]) exceeded in 7 wells;
- Toluene was detected in samples from 37 wells, with the groundwater quality standard (1,000 ppb) exceeded in one well;
- Ethylbenzene was detected in samples from seven wells; a sample from one well exceeded the groundwater quality standard of 700 ppb;
- Total xylenes were detected in samples from 12 wells, with the groundwater quality standard of 10,000 ppb being exceeded in one sample;
- TPH-GRO was detected in 16 well samples but the groundwater quality standard of 7.3 milligrams per liter (mg/l) was not exceeded in any sample;
- TPH-DRO was detected in samples from 42 wells, with and the groundwater quality standard of 1.1 mg/L exceeded in 8 wells.

Data from the latest sampling events however, indicate that groundwater quality standards are exceeded at only five well locations; three for benzene (wells AMI237, AMI182, AMI149) and two for TPH-DRO (wells AMI252 and AMI186).

The Operators documented that improper backflow prevention on piping between tanks and water supply wells effected water quality in a group of benzene-effected wells (at least four wells). Operators are working to determine causes of the low level petroleum hydrocarbon detections in other wells including investigating the use of hydrocarbon-based pipe dope compounds used in setting well pumps, water well drilling techniques, and natural sources. Best Management Practices are also being developed and implemented by the Operators that include requiring: hydrocarbon-free pipe dope in water well applications; cleaning all down-hole equipment before installing in water wells; and, backflow prevention devices and air gaps on all piping that connects tanks and water wells.

Identified Data Gaps

Geomatrix identified several data gaps while evaluating the existing groundwater dataset that result in uncertainty to interpretations and analyses presented in this report. Data gaps are summarized below.

Data Gap	Description and Basis
1	There is a lack of contemporaneous groundwater and surface water elevation data for the PAPA. Currently, water level data are collected over the course of a field season and the existing dataset contains seasonal effects that may affect groundwater flow interpretation, especially at the more localized level.
2	There is insufficient surface water flow data to determine influent/effluent characteristics of rivers. There are no available synoptic flow data, and flow data collected from essential USGS gaging stations do not have overlapping periods of record.
3	There is insufficient data to determine groundwater/surface water interconnection. No monitoring wells are completed in the Alluvium HSU. Water level data collection is too infrequent to discern the response (if any) of the Regional Wasatch Formation HSU to changes in New Fork River stage.
4	There is insufficient aquifer hydraulic property data (hydraulic conductivity, storativity) to determine potential groundwater discharge rates to rivers and groundwater velocity/travel time in the various HSUs.
5	Water level monitoring is too infrequent to detect potential water level decline. Seasonal water level fluctuations cannot be discerned from annual water level measurements and more frequent measurements are necessary to create groundwater hydrographs for the various HSUs. Also, potential changes in hydrostatic pressure are not being monitored in artesian wells near the New Fork River.
6	Mesa and Antelope Springs have not been characterized for flow and water quality. These springs likely issue from saturated zones within the Shallow Wasatch Formation HSU and would be expected to be sensitive to short-term variations in precipitation. Their flow and water quality characteristics should be documented to augment the baseline data set.
7	The hydraulic connection between the Shallow and Regional Wasatch Formation HSUs has not been investigated. Current interpretations are based on information contained on well driller's logs, which can be inconsistent.
8	Confidence in well reference elevation data is low due to the types of instrumentation used to collect data. Accurate positional and reference elevation data is crucial to obtain accurate hydrogeologic interpretations.

Recommended Monitoring Program

Water quality data generated by the current monitoring program adequately describes baseline conditions in the Shallow Wasatch and Regional Wasatch Formation HSUs, and in the New Fork River. Geomatrix recommends changing the current monitoring program to optimize its ability to detect and quantify water resource impacts, as well as increase its efficiency and cost effectiveness. Future monitoring efforts should focus on detecting changes in water quality and water quantity. Suggested goals for the new monitoring program are outlined below.

Water Quantity

- Survey applicable existing and new water wells to a common horizontal and vertical datum by a licensed professional land surveyor.
- Measure water levels on a frequent basis in a subset of domestic, stock, and industrial water wells using pressure transducers equipped with data loggers.
- For all wells being sampled for water quality, measure water levels during a compressed timeframe (1-2 weeks) at a consistent time of each year (e.g. August or September).

- Examine water level data trends annually and investigate the cause of any declining trends noted.
- Compile water usage data for each water supply well within the PAPA on an annual basis.

Groundwater/Surface Water Interaction

To describe the interconnection between the New Fork and Green Rivers, Alluvium HSU, Shallow Wasatch Formation HSU, and Regional Wasatch Formation HSU, river stage and groundwater levels in each HSU should be measured on a frequent schedule. Since none currently exist, monitoring wells would need to be installed in alluvial aquifers adjacent to these rivers. Data collection should be coordinated with USGS activities at existing gaging stations to facilitate data comparison.

Water Quality

- For wells and surface water stations that have previously been characterized for a suite of inorganic constituents (pH, total dissolved solids [TDS], sulfate, chloride, fluoride, and SAR), limit future routine analyses to field measurement of pH, temperature, specific conductance, and TDS.

- Monitor three groups of wells, with each group comprised of one third of all domestic, stock, and industrial wells, on a rotating annual basis for static water level, pH, temperature, specific conductance (SC), and TDS. Wells should be selected so that each of the three groupings represents, to the extent possible, an even areal distribution over the PAPA. Concentration trends should be examined and appropriate action taken to investigate any perceived degradation of water quality.

- Coordinate field measurements of pH, temperature, SC, and TDS at New Fork River monitoring stations with groundwater monitoring activities.

- Sample all industrial wells that previously exhibited petroleum concentrations in excess of an applicable standard on a quarterly basis (or on a schedule that is appropriate based on frequency of use) until the source(s) of petroleum hydrocarbons are determined and appropriate action taken in accordance with federal and state regulations.

- All future analyses for petroleum hydrocarbons (TPH-DRO, TPH-GRO, BTEX) should be conducted using appropriate analytical methods (e.g. EPA Method 8015/8020).

- Establish protocols for collecting representative samples for volatile petroleum hydrocarbon analyses (e.g. BTEX, TPH-GRO) from industrial and stock wells. Current methods include use of submersible electric pumps to collect these samples, which may result in losses of volatile compounds and results that are not representative of groundwater concentrations. Electric submersible pumps may be used to purge wells, but they should not be used for collection of volatile petroleum hydrocarbon samples. Appropriate sample collection equipment includes positive displacement pumps (e.g. pneumatic bladder or piston pumps), discreet interval samplers (e.g. thief sampler), or bailers. Specific sampling depths for each well based on perforated intervals should be established and used consistently. Samples from domestic wells should continue to be collected using the existing pumping systems in order to maintain the integrity of sanitary well seals.

- Sample all new domestic, stock, and industrial wells that meet the 2000 ROD requirements for all parameters in the current SAP (SCCD 2007), then incorporate them into the modified monitoring program.

- Implement Best Management Practices that require: hydrocarbon-free pipe dope in water well applications; cleaning all down-hole equipment before installing in water wells; and, backflow prevention devices and air gaps on all piping that connects tanks and water wells.

1.0 INTRODUCTION

A group of oil and gas producers operating in the Pinedale Anticline natural gas field retained Geomatrix Consultants, Inc. (Geomatrix) to conduct a groundwater study in the Pinedale Anticline Project Area located in west-central Wyoming in Sublette County, near Pinedale, Wyoming. These companies, including Shell Rocky Mountain Production (Shell), Ultra Petroleum Corporation (Ultra), Questar Market Resources (Questar), BP America Production Company (BP), and Yates Petroleum Corporation (Yates) (collectively referred to as the Operators), participate in a groundwater monitoring program that includes their water supply wells, and existing stock water wells, domestic wells, and the New Fork River. The Operators are interested in evaluating the current monitoring program based on a hydrogeologic conceptual model of the area resulting from a comprehensive groundwater study. This report presents findings from the groundwater study and offers recommendations for improving the groundwater monitoring program.

1.1 Project Background and Purpose

The Pinedale Anticline Project Area (PAPA) consists of approximately 198,000 acres principally under the jurisdiction of the USDI Bureau of Land Management (BLM) (**Figure 1, Appendix A**). The Pinedale Anticline Natural Gas field is considered a significant natural gas resource in the United States with recoverable reserves of over 20 trillion cubic feet. To drill and develop natural gas wells a source of fresh water is required. Operators typically install water supply wells (industrial wells) to supply drilling, hydraulic fracturing, dust control, and other water needs. BLM has managed oil and gas development in the PAPA pursuant to their Record of Decision (ROD [BLM 2000a]) for the *Final Environmental Impact Statement (EIS) for the Pinedale Anticline Oil and Gas Exploration and Development Project, Sublette County, Wyoming* (BLM 2000b). The Final EIS made certain recommendations with respect to groundwater resources that were incorporated into the ROD, which required Operators to:

a. Conduct a survey and a complete water analysis (e.g. static water level, alkalinity, salinity, benzene, oil, etc.) of all water wells (industrial, stock and domestic) within a one-mile radius of existing and proposed natural gas development, and annually monitor and maintain a complete record of water analysis of all new water supply wells drilled in the PAPA to evaluate the quality of source options.
b. Develop a groundwater monitoring program to include routine measurement of groundwater levels in existing stock wells and groundwater quality to ensure that wells are not being impacted (drawdown of water table and degradation of quality) beyond their intended use as a result of the proposed project.
c. Submit groundwater reports to BLM annually.

The Operators contracted with the Sublette County Conservation District (SCCD) to develop the groundwater monitoring program and to collect and manage groundwater data necessary to fulfill the requirements of the 2000 ROD. SCCD began inventorying water wells in July 2001 and completed the first annual sampling event during the period of August 2004 to January 2005. Annual monitoring was continued in 2005 (SCCD 2005a,b), 2006 (SCCD 2006a,b) and 2007. SCCD conducts the required monitoring in accordance with a Sampling and Analysis Plan (SAP) developed by SCCD and the Pinedale Anticline Work Group (PAWG), Water Resource Task Group (SCCD 2007). In general, all industrial water supply wells and domestic and stock wells located within a one-mile radius of a gas production well are monitored annually for static water level and general water quality parameters. Wells new to the program are also initially sampled for total petroleum hydrocarbons. Approximately 10 percent of existing industrial wells are sampled for petroleum constituents on an annual basis. Data and information collected by the SCCD are entered by SCCD personnel into a Microsoft Access database designed by SCCD.

In an August 2005 letter to BLM's Pinedale Field Office (**Appendix G**), the Wyoming Department of Environmental Quality (DEQ) expressed concerns about the SCCD/PAWG monitoring program's ability to detect potential impacts to groundwater resources due to uncertainties about the hydraulic connection between wells being monitored and aquifers penetrated by gas wells. DEQ questioned the adequacy of the monitoring program to meet the objectives of the ROD, even though the program fulfills the stated requirements of the ROD (BLM 2000).

In response to a proposal from the Operators for a long-term plan for exploration and development of the PAPA, BLM issued a Draft Supplemental Environmental Impact Statement in December 2006 (BLM 2006), and a Revised Draft Supplemental Environmental Impact Statement (Revised DSEIS) (BLM 2007) in December 2007. The Revised DSEIS indicates that a new groundwater monitoring program will be developed by BLM and DEQ in accordance with the Regional Framework for Water Resources Monitoring to Energy Exploration and Development (USGS 2007a) within six months of issuance of the ROD. The Revised DSEIS makes several recommendations regarding water well installation and future monitoring, including:

- Installation of backflow prevention devices on all wells;
- Installation of water wells using sanitary methods and eliminating use of lubricants containing hazardous substances;
- Testing water quality in all new wells to ensure different classes of groundwater are not being mixed;
- Testing all new wells for major ions and hydrocarbons;
- Running electric logs (presumably only at existing well locations) to characterize shallow geology;
- Requiring Operators to use deeper water bearing zones instead of using Class I groundwater for gas well drilling. (While complying with the WOGCC requirement for minimum drilling water quality of 3,000 parts per million TDS).

The BLM is currently reviewing comments to the Revised DSEIS, analyzing alternatives, and anticipates issuing a Final SEIS in 2008.

The Operators desire to both comply with BLM's 2000 ROD and more fully understand the groundwater system being monitored in the PAPA. Consequently, the Operators issued a Request for Proposal in June 2007 to compile and analyze existing groundwater data in the PAPA with specific objectives of evaluating if aquifers can be correlated, determining any water quality zones, and identifying any relationships that may exist between domestic wells and operator wells. Additional objectives included identifying data gaps and reviewing the current groundwater monitoring program being conducted by the SCCD. Geomatrix was selected to perform the groundwater study and initiated work in August 2007.

1.2 Project Goals and Objectives

The Operators retained Geomatrix to construct a hydrogeologic conceptual model that describes the groundwater system within the PAPA and evaluate the efficacy of the current groundwater monitoring program. Specific objectives of Geomatrix's groundwater study include the following:

1. Compile available existing hydrogeologic and water quality data;
2. Collate data into a central data management system;
3. Analyze existing data and information to develop a hydrogeologic conceptual model that describes the groundwater flow system(s) with regard to recharge, groundwater flow, groundwater/surface water interaction, and water quality;
4. Identify data gaps that should be filled to further the collective understanding of the PAPA's groundwater system(s);
5. Review the current groundwater monitoring program to determine it's efficacy for detecting potential impacts due to oil and gas exploration and development activities; and,
6. Provide recommendations for filling any identified data gaps and improving the current groundwater monitoring program.

1.3 Report Organization

This report presents and discusses key components of a hydrogeologic conceptual model of the PAPA. This introductory section is followed by a review of data sources in **Section 2,** and regional and local physiography and geology in **Section 3**. The climate of the PAPA and vicinity is discussed in **Section 4**. A discussion of surface water hydrology is presented in **Section 5**, followed by groundwater hydrogeology in **Section 6**. Surface water and groundwater quality are discussed in **Section 7**. **Section 8** presents Geomatrix's hydrogeologic conceptual model and **Section 9** is an evaluation of the current groundwater monitoring program in consideration of the conceptual model. In **Section 10**, we identify data gaps and offer recommendations for filling data gaps. **Section 11** provides recommendations for improving the current groundwater monitoring program. References cited in this report are presented in **Section 12**.

Supporting documentation for this report is contained in several appendices. **Appendix A** contains figures and maps. Water level and water quality summary tables are contained in **Appendices B** and **C**, respectively. Water quality figures and charts are presented in **Appendix D**. **Appendices E** and **F** contain a potentiometric surface map in large format and the project database on compact disc, respectively. **Appendix G** contains copies of pertinent regulatory correspondence.

2.0 DATA SOURCES, DESCRIPTION, AND COLLATION

2.1 Sublette County Conservation District Database

Geomatrix researched and accessed environmental data from a variety of sources to complete the groundwater study. This section presents and describes data sources and how the data were managed.

The SCCD began collecting groundwater data in the PAPA in 2001. Data are stored in a Microsoft Access database constructed and maintained by the SCCD. Data contained in the database included:

- Results of the initial field inventory of water supply wells that required monitoring in accordance with the ROD;
- Water well permit information, including ownership, location, depth and a summary table cross referencing permit numbers and SCCD well IDs;
- Well locations determined using survey grade and non-survey (e.g., recreational) grade GPS units;
- Well construction information, including type and size of casing, screened or perforated intervals, and total depth;
- Lithologic descriptions recorded on driller's well logs;
- Static water level measurements; and,
- Water quality sampling results, including field measurements and laboratory analytical results for general chemical parameters and petroleum hydrocarbon compounds. To date, laboratory analytical data has been collected at 167 industrial wells, 50 domestic wells, and 22 stock wells.

In constructing the database, the SCCD identified each well by a unique alphanumeric code related to well type. Alphabetic characters include "AS" for Anticline stock wells, "AMI" for Anticline miscellaneous industrial wells (e.g. Operator water supply wells), and "AD" for Anticline domestic wells. There are variations on this identification system reflecting multiple uses or uncertain use of a few wells (e.g., ADS015). Following the alphabetic characters, individual wells are identified by a three-digit number. For each well type, numbers were selected consecutively by the SCCD in the order they were discovered (e.g. AMI242 and AD115). Geomatrix added additional wells to the database which are reported in U.S. Geological Survey (USGS) documents. These wells are identified according to their USGS nomenclature (e.g., USGS-32-110-13ab01).

Geomatrix amended the SCCD database with additional data mentioned in this section. Queries were also created to retrieve data in a format that supported the various analyses described later in this report. Geomatrix reviewed SCCD data and any apparent anomalous data were identified, examined, and either rejected or retained in the database.

SCCD data are currently only available through June 2007. Therefore, this report does not include any SCCD groundwater quality (e.g. petroleum hydrocarbons) data beyond this date. According to SCCD, data for the second half of 2007 will not be available until August 2008.

Vertical Elevation Discrepancies

While preparing the initial groundwater elevation maps for this study, Geomatrix identified numerous and significant discrepancies between well elevations recorded in the SCCD database and elevations estimated for well locations based on USGS topographical maps. To record geographic position (horizontal coordinates) and well head elevations, the SCCD used survey grade GPS units for approximately 10 percent of the wells and resource or recreational grade GPS units (Trimble® or Garmin® units) for the remaining wells. According to manufacturers, horizontal accuracies for these units are:

- Survey grade GPS – ±6 centimeters
- Trimble GeoExplorer – ±3 meters
- Garmin Map 76 - ± 15 meters

Based on this information, Geomatrix posted final horizontal coordinates for wells and monitoring points in the database using the following order of preference:

1. Survey grade GPS data was used, if available.
2. Trimble GeoExplorer data was preferred over Garmin Map 76 data.
3. Multiple sets of Garmin Map 76 coordinates were available for many locations. For these locations, Garmin Map 76 coordinates were averaged. Anomalous readings were not included in the average.

To determine/select vertical elevations of each individual well or monitoring point in the database, Geomatrix obtained USGS Digital Elevation Model (DEM) (USGS 2001) elevation data using SCCD's GPS horizontal coordinates selected according to the method mentioned above. To meet National Map Accuracy Standards (which DEM data does), 90% or more of the DEM points must be within one-half the map contour interval of the true elevation (USGS 1999). Although this method of assigning well/measuring point elevation has inherent error (e.g., DEM accuracy; accuracy of horizontal GPS coordinates; ignoring well casing stickup height), Geomatrix believes that uniform application of this approach for all wells/monitoring points in the database results in an overall improvement in accuracy. Consequently all figures, cross sections, and analyses that use elevation data were referenced to DEM elevation data.

Limitations for SCCD Static Water Level Data

Static water levels in wells were generally measured by SCCD annually (2004 through 2007) prior to sampling each well. Monitoring occurred throughout the field season (April through November) rather than a specific month each year. Water levels for some wells were measured only once, while other wells have five or more database entries. As such, annual static water level data contained in the SCCD database do not represent a "snapshot" of groundwater conditions across the PAPA, but instead represent an integrated groundwater level condition averaged from the multi-year period of record. For analyses presented in this study, Geomatrix used the average static water level for each well after discarding apparent anomalies. Anomalous entries for individual wells were determined by examining the difference between maximum and minimum values for each well, assuming that large differences (>15 feet) may be due to unnatural factors (e.g. measurement error, pumping before or during measurement).

2.2 Operators

Geomatrix requested and received additional water well permits and water quality data from the Operators that were not included in the SCCD database. Permit information that was not included in the SCCD database was added to the project database, including lithologic and well construction information. Some additional water quality data resulted from DEQ's October 2006 requirement (DEQ 2006) that Operators sample all water supply wells for gasoline-range and diesel-range total petroleum hydrocarbons, and benzene, toluene, ethylbenzene, and xylenes (TPH-GRO, TPH-DRO, and BTEX, respectively), as well as subsequent monitoring efforts through the end of 2007. These additional data included:

- All analytical data collected by Shell, Questar, and BP through the end of 2007.
- Data collected by Ultra through the end of 2007 from three water wells enrolled in DEQ's Voluntary Remediation Program. The remaining Ultra wells are sampled by SCCD and results are not yet available.
- Data collected by the SCCD for Yates from Blue Rim State #2 well.

Geomatrix incorporated these petroleum hydrocarbon water quality data into the project database. Data that were provided electronically in a compatible format were imported directly to the project database to avoid transcription errors. Otherwise, data obtained from the Operators were hand entered and subsequently reviewed for transcription errors.

2.3 Wyoming State Engineers Office Water Rights Database

The Wyoming State Engineers Office (SEO) issues permits for water supply wells and maintains records for permits issued after 1969. Permits were not required before 1969. The SEO operates a searchable web-based (http://seo.state.wy.us/). Geomatrix searched the on-line database to identify permits for water supply wells in the PAPA that contained well logs and subsequently obtained hard copies of the logs from the SEO. Information from these logs was entered into the project database. Static water elevations indicated on SEO permits/well logs were considered during conceptual model development but not explicitly used for any analysis.

2.4 Water Resources Data System – State Climatologist Office

The Water Resources Data System (WRDS) is a clearinghouse of hydrological and climatological data for the State of Wyoming (http://www.wrds.uwyo.edu/). The WRDS maintains a bibliography of water-related publications, reports, papers, and theses, as well as a searchable library. Geomatrix obtained information from WRDS from the following document:

- Wetstein, et al. (1989) reported on a shallow alluvial aquifer just north of the PAPA as part of an irrigation return flow study. The study included installation of monitoring wells, collection of water level data, and development of a numerical groundwater flow model to describe the alluvial system.

2.5 USGS National Water Information System

The National Water Information System (NWIS) is a web-based database created and maintained by the USGS to house and disseminate water resources data collected by the USGS from a network of current and discontinued surface water and groundwater monitoring stations across the United States. Available data includes stream stage, stream discharge, surface and groundwater quality, well locations and total depths, and groundwater level measurements. The NWIS contains data for 169 groundwater wells within or near the PAPA. Of these, static water level data are available for 133 wells and water quality data are available for 30 wells. Where static water elevations were used in various analyses for this study, Geomatrix determined DEM reference elevations based on NWIS latitude and longitude coordinates for each well. Geomatrix also obtained lithologic logs from the USGS for 31 of these wells and entered these data into the project database.

The NWIS also contains information for current and former stream gaging stations located on the Green River, New Fork River, Boulder Creek, and East Fork River. One station on the Green River, three stations on the New Fork River, one station on Boulder Creek, and one station on the East Fork River are relevant to this project. Stream stage and discharge data is available for all six locations. Water quality data is available for five of the six stations. These surface water data, while used in our analyses, were not incorporated into the project database.

2.6 USGS Publications

Numerous USGS publications including open file reports, atlases, and water resource investigations include the PAPA. Publications that are relevant to this project focus on groundwater resources, geology, and oil and gas resource evaluations. Although not exhaustive, the following list describes USGS documents from which information and/or data were obtained for this study.

- Law (1984) compiled geologic information on the gas-bearing formations in the Pinedale Anticline, including geologic structure and stratigraphy.
- Zimmerman and Collier (1985) compiled groundwater data, including well records, well logs, and groundwater chemistry in the Green River Basin.
- Taylor, et. al. (1986) described physiography, precipitation, geology, stratigraphic correlations, and hydrogeologic characteristics of rocks in the Upper Colorado River Basin.
- Glover, et. al. (1998) studied the hydrogeology of Tertiary formations in the Upper Colorado River Basin, which includes the Green River Basin where the PAPA is located. The study includes discussions of the geologic framework, hydrostratigraphy, geochemistry, hydraulic conductivity, groundwater movement, and groundwater recharge/discharge.
- Martin (1996) described the hydrogeology of the Green River Basin including the geologic framework and various aquifers, and presented a numerical groundwater flow model for the Basin.
- Chafin and Kimball (1992) describe the groundwater geochemistry of the Wasatch Formation in the Upper Green River Basin, Sublette County, Wyoming and included a groundwater potentiometric map for the basin.
- Welder (1968) presents information on geology, water-bearing potential of individual aquifers, water quality, hydrology, and precipitation for the Green River Basin.
- Wetstein and others (1989) studied the New Fork River alluvial aquifer just north of the PAPA as part of an irrigation return study. The study included installation of groundwater monitoring wells, aquifer testing, and development of a numerical computer (MODFLOW) model.
- Lohwam and others (1985) compiled water resources data for the Rocky Mountains coal-producing region that includes Wyoming, Colorado, Idaho, and Utah. The report includes groundwater quantity and quality data for the Wasatch Formation.

2.7 Bureau of Land Management

The BLM is the lead governmental agency for management of the PAPA since the vast majority of land within the production area is public land managed by BLM. The BLM has regulatory responsibility for all federally-owned mineral leases, which account for approximately 80 percent of the PAPA (BLM 2006). The following information were obtained from BLM:

- Dynamac (2002) prepared a Preliminary Ground Water Characterization Study of the PAPA for the BLM to support resource management decisions. The report described the hydrogeology and groundwater chemistry of the PAPA.

- BLM (2000b) prepared a Final Environmental Impact Statement for the Pinedale Anticline Oil and Gas Exploration and Development Project in May.

- BLM (2000a) prepared a Record of Decision for the Final Environmental Impact Statement for the Pinedale Anticline Oil and Gas Exploration and Development Project in July.

- BLM (2006) prepared a Draft Supplemental Environmental Impact Statement for the Pinedale Anticline Oil and Gas Exploration and Development Project in December.

- BLM (2007) prepared a Revised Draft Supplemental Environmental Impact Statement for the Pinedale Anticline Oil and Gas Exploration and Development Project in December.

BLM is also the ultimate repository and distributor for the SCCD PAPA database.

3.0 STUDY AREA DESCRIPTION

The PAPA is located in Sublette County just south of Pinedale, Wyoming (**Figure 1**). Oil and gas exploration and production targets natural gas accumulations in a subsurface geologic trap called the Pinedale Anticline. The uppermost gas-bearing geologic formations of economic significance are located approximately 8,000 feet below ground surface (Law 1984). The Anticline Crest is approximately two to three miles wide, and is oriented northwest to southeast parallel to the Wind River Range located to the east. The PAPA encompasses an area of approximately 308 square miles, and is about 12 miles wide by 26 miles long.

3.1 Physiography and Geologic Setting

The PAPA is located within the upper Green River Structural Basin, which is part of the Upper Colorado River Basin, between the Wind River Range to the east and north and the Wyoming Range to the west (**Figure 1**). The northern portion of the PAPA is dominated by a topographic feature referred to as The Mesa, a pediment that, at over 7700 feet elevation, is approximately 500 feet higher than the Town of Pinedale (**Figure 2**). The PAPA is bisected by the New Fork River just south of The Mesa. The elevation of the New Fork River south of The Mesa is approximately 6850 feet. The northern portion of the PAPA is approximately bordered by the Green River on the west and the New Fork River on the east/northeast. South of the New Fork River, the landscape is characteristic of semi-arid environments, with sparse vegetation covering ridges and buttes (elevation generally between 7200 and 7400 feet) that are dissected by numerous ephemeral drainages.

The Green River Structural Basin is reported to have formed in the Laramide Orogeny during the late Cretaceous Period by uplift of mountain ranges bordering the basin, thrusting at basin margins, local folding and faulting, and subsidence of the basin's depositional centers (Roehler 1992). Deposition of sediments comprising the Tertiary geologic formations of interest in this study occurred throughout the Laramide Orogeny as depositional centers subsided. Since the end of the Eocene Epoch, the Green River Basin has been only slightly modified by regional uplift, normal faulting, volcanism, and erosion (Roehler, 1992).

Figure 3 is a simplified regional map of sedimentary geologic formations. Cretaceous and older crystalline and sedimentary rocks occur at the basin margins, while the near-surface geology of the Green River Basin interior is comprised of Tertiary sedimentary rocks. Within and adjacent to the PAPA, bedrock geology consists primarily of the lower Tertiary Wasatch and Green River Formations. Geologic descriptions of the Wasatch and Green River formations were obtained from previous studies (Chafin and Kimball, 1992; Welder, 1968; Glover et al, 1998; Roehler, 1992; Martin, 1996). The Wasatch Formation primarily consists of lenticular arkosic sandstone beds, representing river channel deposits, and sandy shale and siltstone representing overbank and floodplain deposits. The Wasatch Formation was deposited in a piedmont environment in an internally-drained depositional basin contemporaneous with the Green River Formation, which represents lacustrine (lake) deposition. The Wasatch Formation is approximately 7,000 feet thick in the Pinedale area (Martin, 1996). Due to changes in the position of the lake shoreline over time, Wasatch sediments intertongue with Green River sediments (Glover et al, 1998). The Green River formation is comprised predominantly of lacustrine (lake) deposits of fine sandstone, siltstone, and shales, and contains abundant fossils assemblages and deposits of coal, the evaporite mineral trona (hydrated sodium bicarbonate carbonate). The Laney Member of the Green River Formation, located south and east of the PAPA, contains oil shale at some locations (Welder, 1968).

A generalized geologic cross section perpendicular to the Pinedale Anticline (adapted from Law, 1984) is shown in **Figure 4**. The cross section illustrates the relative stratigraphic and structural features of the Pinedale Anticline and surrounding area. The Wasatch Formation overlies the Tertiary Fort Union Formation. Beneath the Fort Union Formation is an unnamed Tertiary unit which serves to seal the underlying natural gas-bearing Lance and Erickson Sand Formations. The total thickness of Tertiary rocks overlying the Cretaceous gas-bearing formations is approximately 8000 feet. The Pinedale Anticline structure expressed in the Cretaceous rocks is associated with a thrust fault that parallels and may be rooted to the Wind River Thrust Fault to the east.

The Wasatch Formation generally underlies the entire PAPA (**Figure 5**). Outcrops are present beneath The Mesa, in steep-sided coulees and in various locations along the New Fork River valley and consist of horizontal to sub-horizontal sandstone, siltstone, and shale beds. Overlying the Wasatch Formation on The Mesa are coarse terrace gravels of Quaternary age (**Figure 5**). These are alluvial glacial outwash deposits (sand, gravel, cobbles) originating from the Wind River Range (BLM 2007). Information from available water well logs indicates the terrace gravels are approximately 10 to 35 feet thick. The slopes of The Mesa and intermittent drainages are covered by varying thicknesses of colluvium and alluvium derived from upslope terrace gravels and erosion of the Wasatch Formation. Available water well logs indicate these colluvial/alluvial materials can be as much at 38 feet thick. Alluvium (predominantly unconsolidated sand, gravel, and some clay) occurs in the valleys of the Green River, New Fork River and their tributaries. Information from available water well logs indicates the following thicknesses of alluvium adjacent to the New Fork River: 52 feet south of Pinedale; 80 feet near Boulder; and, 12 feet near the confluence of the Green River and New Fork River (**Figure 5**).

Figures 6, **7**, **8**, and **9** are hydrogeologic cross sections based on information obtained from driller's logs for water supply wells located within the PAPA. Section locations are shown on **Figure 2**. Cross section A-A' (**Figure 6**) is a west-southwest to northeast cross section from the Green River, across The Mesa and to the New Fork River south of Pinedale. Cross section B-B' (**Figures 7** and **8**) approximately traverses the axis of the Pinedale Anticline from northwest to southeast. Cross section C-C' (**Figure 9**) runs southwest to northeast across the anticline south of the New Fork River, roughly paralleling the Blue Rim.

Cross sections shown in **Figures 6**, **7**, **8**, and **9** illustrate the heterogeneous character of the Wasatch Formation, which is composed primarily of relatively thin, discontinuous arkosic sandstone beds embedded in relatively thick shale units. Sand and clay units at depth are indicated on some logs (e.g., wells AS013, AMI029, and AMI018 on cross section B-B'; **Figures 7** and **8**) that probably represent friable sandstone beds and soft shale, respectively. More detailed descriptions of the sandstone and shale units are found in Voegeli (1971). Wasatch sandstone units at the El Paso Natural Gas Pinedale No. 5 and Wagon Wheel No. 1 wells, located south of the New Fork River in the Township 30N, Range 108W, Section 5 (near AMI266) are described as arkosic, unconsolidated (e.g. friable), medium to very coarse grained, angular to subangular, and poorly sorted (Voegeli 1971). The lithologic log for Wagon Wheel No. 1 describes the Wasatch Formation shale beds as soft and containing bentonite (Voegeli 1971).

Geomatrix reviewed well driller's logs, published geologic reports, and cross sections prepared during this study in an attempt to correlate lithologic units in the Wasatch Formation across the PAPA. Based strictly on lithologic data and information available to us from water well logs, it appears that individual units are not laterally continuous over distances of hundreds of feet.

4.0 CLIMATE

Figure 10 illustrates the distribution of average annual precipitation for Sublette County. Precipitation in the mountains northeast and west of Pinedale is significantly greater than in the lower portions of the county which includes the PAPA. Statewide, precipitation averages between 12 and 13 inches annually (Western Regional Climate Center, 2007). Based on available SNOTEL data, the mountain ranges in vicinity of Pinedale receive between 20 and 24 inches of annual precipitation, while Pinedale receives an average of 10.82 inches of annual precipitation (Western Regional Climate Center, 2007). Key climatic data for Pinedale is summarized in **Table 1**. Average monthly data indicates more precipitation occurs during the period May through September (5.9 inches) than during the period October through April (3.9).

Table 1 Summary of Monthly Climate Data for Pinedale, Period of Record 8/1/1948-4/30/2007

Measured Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	26	30	38	49	61	71	79	77	68	56	38	28	51.7
Average Min. Temperature (F)	-1.1	1.1	9.7	21	29	37	41	38	30	22	12	1.4	20
Average Total Precipitation (in.)	0.6	0.5	0.6	0.9	1.6	1.2	1	1	1.1	0.8	0.7	0.7	10.82
Average Total Snowfall (in.)	12	9.5	8.2	6	2.4	0.3	0	0	0.7	2.6	9	11	61
Average Snow Depth (in.)	8	9	6	1	0	0	0	0	0	0	2	5	3

Reference: Western Regional Climate Center, 2007.

Annual precipitation data for the station at the Daniel Fish Hatchery, located approximately 13 miles west of Pinedale, are summarized on **Figure 11** (data from the Pinedale meteorological station was not used due to a large amount of missing data). **Figure 11** illustrates below normal precipitation for four of the six years between 2001 and 2006.

Mean evaporation potentials for Wyoming calculated from pan evaporation data range from 39.1 inches to 47.9 inches (Wyoming Climate Atlas, 2004). No published evaporation potential data for Pinedale was found. The low average annual evaporation potential (39.1 inches) is approximately four times higher than the mean annual precipitation amount at Pinedale,. Although the total annual potential evapotranspiration exceeds total annual precipitation, infiltration of precipitation can occur when evapotranspiration rates are low. A comparison of evaporation potential and the average precipitation amount indicates the majority of groundwater recharge does not occur via direct infiltration of precipitation.

5.0 HYDROLOGY

Figures 1 and **2** show water courses at and in the vicinity of the PAPA. Perennial rivers within and adjacent to the PAPA are:

- Green River located adjacent to the western PAPA boundary in the north.
- New Fork River located adjacent to the eastern PAPA boundary in the north, and bisecting the PAPA from approximately east to west.
- East Fork River, a tributary to the New Fork River, which enters the PAPA from the east near the Town of New Fork.

Headwaters for these rivers are located to the north and east in the Wind River Range. The confluence of the East Fork and New Fork Rivers is within the PAPA, near the east-central PAPA boundary (**Figures 1** and **2**). The New Fork River joins the Green River approximately six miles west of the PAPA. The Green River continues flowing southward through Fontenelle Reservoir and Flaming Gorge Reservoir, and ultimately discharges to the Colorado River in Utah.

Several perennial streams join the New Fork River east and north of the PAPA, including Duck Creek, Pine Creek, Pole Creek, and Boulder Creek (**Figure 2**). Numerous ephemeral drainages are present in the PAPA, many of which Geomatrix observed to be dry in August 2007. No lakes are present within the PAPA; however, several significant lakes occur north and northeast of the PAPA, including Freemont Lake and Boulder Lake near the western front of the Wind River Range. Several small water storage reservoirs are present within the PAPA where ephemeral drainages are dammed. Several irrigation ditches inside the PAPA divert water from and are generally parallel to the Green and New Fork Rivers. A few springs occur within the PAPA, including Mesa Spring and Antelope Spring (**Figures 2** and **6**); however, these likely flow at relatively low rates. Flow from Mesa Spring, located along the west side of The Mesa (**Figures 2** and **6**), was estimated to be 0.25 gallons per minute (gpm) in August 2007.

Table 2 lists mean monthly discharge data reported by the USGS for stream gaging stations on the New Fork River, East Fork River, Boulder Creek, and Green River (NWIS 2007). Lowest monthly flows in the New Fork River generally occur during the period of December through March, and highest flows occur in June, followed by July and May. Low mean monthly flows for the New Fork River at Pinedale and Big Piney are approximately 25 and 200 cubic feet per second (cfs), respectively. High mean monthly flows for the New Fork River at Pinedale and Big Piney are approximately 200 and 3,000 cfs, respectively. Low mean monthly flows in the Green River near Daniel and La Barge are approximately 100 and 500 cfs, respectively; whereas high mean monthly flows at these Green River stations are approximately 1,800 and 5,500 cfs, respectively.

Mean monthly discharge data for the three New Fork River gaging stations (**Table 2**) show a consistent increase from upstream to downstream. However, Geomatrix could not locate synoptic flow data for these stations (and Boulder Creek and East Fork River) for which to compare single base flow measurements on a common day.

Table 2 Mean Monthly Stream Discharge at USGS Gaging Stations

USGS Gaging Station	Period of Record	Mean Monthly Discharge (cubic feet per second)											
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
New Fork River near Pinedale	10/1/1938 -11/30/1944	23	24	44	93	63	203	176	46	31	48	40	31
New Fork River near Boulder	10/1/1914 -10/1/1969	106	108	121	243	578	1,580	1,010	337	175	167	148	119
Boulder Creek near Boulder	10/1/1903 -12/30/1932	22	23	24	38	316	1060	355	39	19	22	24	22
East Fork River at New Fork,	10/1/1904 -9/30/1932	40	41	48	83	447	941	188	64	54	58	51	44
New Fork River near Big Piney	10/1/1954 -9/30/2006	200	208	272	430	1,160	2,920	1,580	566	368	372	320	238
Green River at Warren Bridge, near Daniel	10/1/1931- 9/30/1906	109	109	124	289	1,020	1,780	1,240	528	299	198	145	124
Green River near La Barge	10/1/1963 - 9/30/1906	454	483	724	1,380	2,790	5,520	3,290	1,390	854	806	723	520

Note: USGS = U.S. Geological Survey. See **Figure 2** for station locations.
Source: USGS NWIS, 2007b

Geomatrix performed a base flow analysis using USGS flow data from gaging stations on Boulder Creek near Boulder, East Fork River near New Fork, and New Fork River stations near Boulder and Big Piney (**Figure 2**). The purpose of this analysis was to evaluate the effluent (gaining from groundwater) or influent (losing to groundwater) nature of New Fork River in the PAPA. Base flow conditions are approximated when contributions from runoff (e.g. rainfall or snowmelt) and withdrawals (e.g. irrigation diversions) are negligible. At the PAPA, these conditions are expected to occur during winter months. For this analysis, Geomatrix approximated base flow by using the 90th percentile of average daily discharge for the month of January for the period of record for each of the stations. These average flows are:

- New Fork River near Boulder: 143 cfs
- Boulder Creek near Boulder: 34 cfs
- East Fork River near New Fork: 55 cfs
- New Fork River near Big Piney: 261 cfs

Based on available flow data for January, there is a gain in average stream base flow at the Big Piney (downstream) gaging station of approximately 30 cfs that is not accounted for by summing average stream flows at the three upstream stations (New Fork River, East Fork River, and Boulder Creek). This analysis suggests the New Fork River is an influent stream (i.e., gains flow from groundwater) in this portion of the PAPA and also supports conclusions of previous studies (e.g., Martin, 1996) that identified the upper Green River and its tributaries to be gaining streams. Supporting lines of evidence for the gain in New Fork River flow from groundwater are discussed in the following section.

6.0 HYDROGEOLOGY

This section presents hydrogeologic characteristics of the PAPA. Included below are discussions of the three principal hydrostratigraphic units we identified, hydraulic characteristics of the units, groundwater recharge and discharge areas, and groundwater flow in the PAPA.

6.1 Hydrostratigraphic Units and Hydraulic Characteristics

Groundwater tapped by various industrial supply, stock, and domestic wells in the PAPA primarily occurs in sand and sandstone units of the Wasatch Formation, and in alluvial material associated with the New Fork and Green Rivers. Hydrostratigraphic units presented below are combinations of geologic units based on their defining hydraulic characteristics and interconnection. Geomatrix identified the following hydrostratigraphic units (HSUs) for the PAPA:

- Shallow Wasatch Formation;
- Regional Wasatch Formation; and,
- River Alluvium.

There is no evidence, based on a review of available drilling logs, that terrace gravel or alluvial material on The Mesa are significant to supply water for industrial, stock or domestic purposes. No records were found that indicated wells are completed in or open to this material.

The occurrence and characteristics of each hydrostratigraphic unit are discussed below.

Shallow Wasatch Formation HSU

Within the PAPA, the Shallow Wasatch Formation HSU is generally present above the Green River and New Fork River valleys. Most stock wells are completed in the Shallow Wasatch Formation HSU and are relatively shallow when compared to industrial water well depths. The average bottom elevation for stock wells is 7050 feet above mean sea level (amsl), compared to an average bottom elevation of 6582 feet amsl for industrial wells. Based on available information largely obtained from well driller's logs, most stock wells are completed in or at least open to what are apparently laterally discontinuous water-bearing zones within the Shallow Wasatch Formation. Static water elevations in stock wells are generally elevated relative to industrial wells.

Cross sections A-A', B-B', and C-C' (**Figures 6** through **9**) all illustrate examples of laterally discontinuous water-bearing sandstone units or lenses within finer-grained siltstone or mudstone/shale units in the Shallow Wasatch Formation. For example, stock wells AS036 and AS007 (cross section A-A', **Figure 6**) are all completed at elevations considerably higher than adjacent industrial wells AMI140, AMI029 and AMI019, and static water elevations for these shallow stock wells are elevated compared to the industrial wells. Furthermore, the well log for industrial well AMI140 (**Figure 6** and **Appendix F**) indicates the presence of a water bearing sandstone unit at an elevation of approximately 7350 feet, then dry sandstone units over a several hundred foot interval, and finally water-bearing sandstone units at an elevation of approximately 6700 feet amsl. Other examples of wells where drillers logs indicate the occurrence of shallow water bearing units underlain by units that were not noted as bearing water are wells USGS-32-109-05db01 (cross section B-B', **Figure 8**) and USGS-30-108-20ba and AS001 on cross section C-C' (**Figure 9**).

Based on information from well driller's logs, the Shallow Wasatch Formation HSU does not appear to be continuously saturated and may be separated from the underlying Regional Wasatch Formation HSU by unsaturated intervals at some locations. Hydraulic properties of the saturated sandstone units are expected to be similar to those of the Regional Wasatch Formation HSU, which is discussed below.

Three springs are shown on USGS topographic maps within the PAPA. Two are located in the southeast portion of the PAPA at an elevation of approximately 7300 feet. These two springs were not observed during field reconnaissance for this study. The third, Mesa Spring, is located on the western slope of The Mesa at a slope break at an elevation of approximately 7260 feet (**Figure 2**). In August 2007, Geomatrix observed a flow of approximately 0.25 gpm issuing from a pipe inserted into the hillside that presumably collected water from the spring. The area adjacent to the spring was damp and vegetation was relatively abundant, indicating that additional groundwater is discharging and being evapotranspired. Glover et. al. (1998) states that springs and seeps in the Green River Basin generally represent discharge from local flow systems or are topographically elevated and represent discharge from perched zones located above low permeability units. Springs identified within the PAPA occur at elevated topographic positions and likely represent discharges of groundwater perched above fine grained mudstone and siltstone (e.g., contact springs) such as those observed and discussed above.

Regional Wasatch Formation HSU

The Regional Wasatch Formation HSU consists of laterally and vertically discontinuous porous sandstone beds interbedded with less permeable shale, siltstone, and mudstone. Glover et. al. (1998) indicates that the Regional Wasatch Formation in the northern portion of the Green Basin is unconfined and water levels represent water table conditions. Due to expected hydraulic conductivity contrasts between shale and sandstone units, and the discontinuous nature of the individual sandstone beds, it is probably more accurate to describe the system as semi-confined or as individual semi-confined sandstone units sandwiched between or embedded in leaky confining units (shale, siltstone, mudstone).

Literature values of hydraulic conductivity are reported in Chafin and Kimball (1992), Martin (1996), and Lohwam et al. (1985). The estimated hydraulic conductivities for the Wasatch Formation presented by Chafin and Kimball (1992) range from 0.2 feet per day (ft/day) to 0.8 ft/day based on age dating of groundwater in various parts of the Upper Green River Basin and measuring the corresponding time of travel. Higher values are associated with basin margins due to a relative abundance of coarse sediments near source areas, while lower values are associated with relatively fine-grained sediments in the central and southern portions of the Basin. Martin (1996) presents a hydraulic conductivity range of 0.03 to 2100 ft/d, with a median value of 8.7 ft/d based on results of 186 specific capacity and drill stem tests. Geomatrix conducted a single well, stepped pumping test at North Mesa 4-7 (AM1140) in October 2006. Geomatrix estimated a transmissivity of 160 square feet per day (ft^2/day) and a corresponding hydraulic conductivity of 3.48 ft/day. **Table 3** summarizes reported hydraulic property information for the Wasatch Formation.

Table 3 Summary of Wasatch Formation Hydraulic Properties

Source	Hydraulic Conductivity	Transmissivity	Comments
Chafin and Kimball (1992)	0.2 to 0.8 ft/d	---	Based on time of travel calculations.
Martin (1996)	0.03 to 2100 ft/d	---	Based on 187 specific capacity tests.
	<18 ft/d	---	Simulated for numerical model.
Geomatrix (2006)	3.48 ft/d	160 ft^2/day	Based on a 6.76-hr stepped pumping test at well Mesa 4-7; pumping rate of 21 to 42 gpm; 67 feet of drawdown observed.

River Alluvium

None of the water supply wells for which data are available are completed in the River Alluvium HSU, although numerous domestic wells penetrate alluvium and are completed in the underlying Wasatch Formation. River alluvium on available well logs is generally described as saturated sand and gravel ranging in thickness from 12 feet near the confluence of the Green and New Fork Rivers to 80 feet near the Town of Boulder. Groundwater most likely occurs under water table conditions within alluvium and is hydraulically connected to both the rivers and streams with which it is associated and the underlying Wasatch Formation.

No aquifer property information is available for alluvium in the PAPA. Wetstein and others (1989) reported that hydraulic conductivities of alluvial material along the New Fork River north of the PAPA ranged from 2 to 1018 ft/day; however, the authors noted that during their pumping tests static water levels in two wells could not be drawn down with their equipment (1/2 HP submersible pump, 16 gpm maximum pumping rate). Wetstein and others (1989) used hydraulic conductivities ranging up to 4000 ft/day in the numerical model they developed and calibrated for their study.

6.2 Groundwater Flow

6.2.1 Groundwater Recharge and Discharge Areas

Previous studies of the Green River Basin indicate that primary recharge to Tertiary aquifers occurs at basin margins where these formations are exposed at land surface (Martin 1996; Glover et. al., 1998; Chafin and Kimball, 1992). **Figures 12** and **13** show reported groundwater recharge areas in the vicinity of the PAPA. **Figure 12** is adapted from Martin (1996) and shows groundwater recharge specifically to the Tertiary aquifers that were the focus of his study. The northwestern portion of the Tertiary aquifer recharge area is shown to receive greater than 2.5 inches of annual recharge, while the northeastern portion of the PAPA receives less than 0.5 inches of recharge annually. No recharge is shown for the southwestern portion of the PAPA. **Figure 13** is adapted from the Wyoming Ground Water Vulnerability Assessment Handbook (Hamerlinck et. al., 1998) and shows general groundwater recharge patterns for Sublette County. Approximately 2.8 inches of recharge is indicated for The Mesa and zero to 0.5 inches of recharge of other areas of the PAPA. **Figure 13** also shows recharge of 0.5 to 1.5 inches for areas along the Green and New Fork Rivers, which is presumably indicative of recharge to shallow alluvial aquifers and not the Wasatch Formation HSUs.

From the principal recharge areas, groundwater in the Regional Wasatch HSU generally flows southwest from the Wind River Range, east from the Wyoming Range, and south toward the central and southern portions of the Green River Basin (Chafin and Kimball, 1992; Lowham et. al., 1985). Martin (1996) indicates that ground-water flow in the Regional Wasatch Formation HSU occurs along short, long, and basin-length flow paths. Glover et. al. (1998) estimate that total groundwater recharge in the upper Green River is 138 cubic feet per second (cfs). Groundwater discharge to the upper Green River and its tributaries above Fontenelle Reservoir occurs at a rate of approximately 94 cfs (Glover et. al., 1998).

6.2.2 Static Water Elevations

There are two sources for static water elevations used in this study:

- Measurements obtained from the National Water Information System (NWIS, 2007) for wells used in USGS studies. These data generally consist of single measurements obtained during the 1960s and 1970s, although more recent data exist and multiple measurements are available for some wells. Several USGS wells are present within the PAPA; however, most are located outside of but in the general vicinity of the PAPA.
- Measurements obtained from the SCCD database. These data consist of measurements obtained by SCCD personnel from 2001 through 2007 in various wells being monitored in general accordance with BLM's 2000 ROD.

Static water level elevations used in the following analyses were derived using DEM surface reference elevations and either an average of water level measurements (sans erroneous measurements) or one time measurements, as applicable (see **Section 2**). Water level data used in analyses by Geomatrix are presented in **Appendix A**.

6.2.3 Vertical Gradients

Vertical groundwater gradients are often associated with groundwater recharge and discharge areas. Groundwater recharge areas are typically characterized by downward-directed vertical gradients, while vertical gradients in discharge areas are generally directed upward. The PAPA is located adjacent to the principal upgradient recharge area for the Regional Wasatch Formation HSU (**Figures 12** and **13**). The general direction of groundwater movement in the Regional Wasatch Formation HSU is from northeast to southwest, with some groundwater discharge occurring along portions of the Green River and New Fork River based on information from previous studies (see **Section 6.2.1**). Based on hydraulic head differences in the Shallow and Regional Wasatch Formation HSUs and local recharge on the Mesa and Blue Rim, groundwater flow in the Shallow Wasatch Formation HSU is primarily directed downward.

Geomatrix analyzed static groundwater elevations for wells at the PAPA to determine vertical components of groundwater flow. These types of analyses are best performed with data from wells that are in close proximity to one another and that are completed to various depths in order to minimize the effect of horizontal gradients. However, most wells in the PAPA are typically separated by distances greater than one mile. **Figure 14** illustrates the relationship between static groundwater elevations and well bottom elevations for all wells in the PAPA study area, and includes reference lines depicting approximate New Fork River stage near Pinedale and south of The Mesa. The majority of groundwater elevations in industrial supply wells are between 6900 and 7000 feet amsl; whereas, the New Fork River stage is within an elevation of about 6860 to 7160 feet amsl. Wells displaying static water elevations greater than 7000 feet are generally located in the northern part of the PAPA in the vicinity of Pinedale. **Figure 14** also shows that groundwater elevations do not correlate to well depth for wells (principally industrial supply wells) completed below an elevation of approximately 6700 feet amsl. This suggests that the horizontal component of groundwater flow for these wells is more dominant than the vertical component for the majority of the study area. Stock and domestic wells depicted on **Figure 14** show the affects of horizontal gradients. Because stock and domestic wells have less yield requirements than the industrial water supply wells, their yields can typically be satisfied at shallower depths. Consequently for stock and domestic wells, lower static water elevations generally correspond to lower well bottom elevations (**Figure 14**); however, the correlation does not appear to be due to significant vertical gradients.

Figure 15 illustrates relationships between well bottom elevation and average static water elevation for subsets of wells located north, south, and adjacent to the New Fork River in the central portion of the PAPA. Wells included in the north area subset are AMI078, AMI079, AMI122, AMI123, AMI124, AMI130, AMI259, and AMI276, which are located approximately 1.25 miles north of the New Fork River. Wells included in the south area subset are AMI135, AMI198, AMI203, AMI234, AMI235, and AMI275. Wells shown near the New Fork River are AMI191, AM1132 and ADS004.

Static water elevations in wells presented on both **Figures 14** and **15** exceed stream stage in the New Fork River south of The Mesa, indicating there is a groundwater potential from the Regional Wasatch Formation HSU to the river. Vertical gradients directed upward should be apparent in wells located close to the river. However, there are few wells with locations and screened intervals conducive to this type of analysis. Furthermore, several industrial supply wells near the New Fork River are reported to be flowing wells (artesian) but the shut-in pressures have not generally been measured. Data for a vertical gradient analysis, however, are available for three wells near the New Fork River (wells AMI191 [Geomatrix measured a shut-in pressure of approximately 11 pounds per square inch at well AMI191in September, 2007], AMI132, and ADS004; **Figure 15**). Recognizing that the analysis uses a limited data set, **Figure 15** indicates an apparent relationship between well bottom elevation and static water elevation, whereby an upward-directed gradient of approximately 0.12 ft/ft is apparent in these three wells. This supports the observation that groundwater in the Regional Wasatch Formation HSU is discharging to the New Fork River in the central portion of the PAPA.

6.2.4 Horizontal Flow

Figure 16 is an estimated potentiometric surface of the Regional Wasatch Formation HSU based on the average of available static water elevations measured by SCCD at each well over the period between 2001 and 2007, and available data for USGS wells. Groundwater flow is generally directed from the northeast to the southwest, consistent with the Wind River Range being a principal source of groundwater recharge for the Regional Wasatch Formation HSU. Potentiometric lines south of the New Fork River in the southern half of the PAPA are roughly perpendicular to the river indicating west-southwesterly flow, with two exceptions:

1. Potentiometric lines converge with the New Fork River in the central portion of the PAPA, indicating localized discharge of groundwater to the New Fork River.

2. An apparent groundwater divide/ridge is evident under Ross Ridge and Blue Rim. Although a source of groundwater recharge in this area is not identified by previous researchers on **Figures 12** and **13**, this upland may be an area of secondary groundwater recharge for the Regional Wasatch Formation HSU.

In the northern portion of the PAPA, groundwater flow ranges from southwesterly to southeasterly (**Figure 16**). In the northeastern portion of the PAPA, potentiometric contours are oriented northwest to southeast. Except for the 7150 contour, potentiometric lines are not deflected by the

New Fork River suggesting the New Fork River is perched above the Regional Wasatch Formation HSU as shown on **Figure 6** (cross section A-A'). A prominent groundwater ridge occurs under The Mesa suggesting groundwater recharge from the north and/or from The Mesa (see **Figures 12** and **13**). Groundwater flows to the south, southwest, and southeast in this area.

On the western side and in the central portion of the PAPA, potentiometric lines converge on the Green and New Fork Rivers. This suggests that groundwater from the Regional Wasatch Formation HSU aquifer discharges to surface water in these areas.

Horizontal hydraulic gradients range in the PAPA from approximately 0.01 to 0.002. Gradients are steepest along with the northeastern PAPA boundary nearest the base of the Wind River Range and decrease to the southwest.

7.0 WATER QUALITY

7.1 Literature Review

Relatively high quality groundwater characterized by low dissolved solids typically occurs in recharge areas near basin margins. Through dissolution and ion exchange reactions, the concentration of total dissolved solids (TDS) increases and the major ion chemistry of groundwater changes along groundwater flow paths directed toward the central and southern parts of the basin. Chafin and Kimball (1992), who studied groundwater geochemistry of the Wasatch Formation in the Upper Green River Basin, found that TDS concentrations increase and ion exchange reactions cause sodium concentrations to increase while calcium and magnesium decrease along groundwater flow paths. Glover and others (1998) found:

- Concentrations of total dissolved solids (TDS), carbonate/bicarbonate, sodium plus potassium, and sulfate increase in Wasatch groundwater along flow paths from basin margins inward;
- Calcium and magnesium concentrations decrease along flow paths; and,
- Inner basin water with TDS >3000 milligrams per liter (mg/L) is dominated by sodium and chloride ions (presumably due to ion exchange processes).

Welder (1968) found that specific conductance generally increases from north to south across the study area along groundwater flow paths and continues to increase to the south throughout the Green River Basin. Lohwam et. al. (1985) reported that elevated TDS and fluoride concentrations are common in the regional study area that includes the Upper Green River Valley.

7.2 Available Data

Groundwater quality data are available from the SCCD database, Operators, the USGS NWIS, and USGS publications authored by Welder (1968), Zimmerman and Collier (1985), Chafin and Kimball (1992), and Glover et al. (1998). Analyses presented below primarily use analytical data from SCCD, Operators, and NWIS. Water quality data from the SCCD database and Operator-provided data are summarized in **Appendix C** and presented on various charts in **Appendix D**. **Section 7.4** below contains a more detailed description of water quality data contained in the SCCD database.

7.3 Monitored Parameters

The SCCD, in consultation with the Operators, DEQ, PAWG, and BLM, developed a SAP (SCCD 2007) for the PAPA that addresses data collection types, frequencies, and procedures. Types of groundwater quality data collected by SCCD on behalf of the Operators are summarized in **Table 4**.

Table 4 Parameters Monitored by SCCD

Parameter	Analytical Method
pH	Field meter
Conductivity	Field meter
Temperature	Field meter
Alkalinity	EPA -A2320 B
Salinity	Calculated
Fluoride	EPA A4500-F C
Sulfates	EPA E200.7
Chlorides	EPA A4500-Cl B
Calcium	EPA E200.7
Magnesium	EPA E200.7
Total Dissolved Solids	EPA A2540 C
Sodium	EPA E200.7
Potassium	EPA E200.7
Anion/Cation Balance	Calculated
Sodium Adsorption Ratio	Calculated
Total Petroleum Hydrocarbons	EPA Method 1664A

SCCD collects samples according to protocols contained in the following documents:

HydroGeo, Inc., 2004. Groundwater Monitoring Protocol Manual, Pinedale Anticline Project .

ASTM Standard D4448-01, Standard Guide for Sampling Groundwater Monitoring Wells, 1985.

According to the SAP, all accessible wells are initially sampled for all parameters listed in **Table 4**. Wells are re-sampled annually for general chemistry (i.e. all **Table 4** parameters except petroleum hydrocarbons) at a minimum. Samples collected for petroleum hydrocarbon analysis are at the discretion of BLM and SCCD. Water wells known to have elevated concentrations of petroleum hydrocarbon constituents are re-sampled annually until directed otherwise by USBLM. Up to 10 additional wells, at the discretion of the SCCD and BLM, may be sampled annually for total petroleum hydrocarbons (TPH).

In 2006, DEQ was informed that four Operator-owned water wells became impacted with petroleum hydrocarbons when water stored in tanks temporarily connected to the wells flowed back into the wells due to inadequate backflow prevention. In a letter dated October 27, 2006 (DEQ 2006) (**Appendix G**), DEQ required all PAPA Operators to:

1. Identify all water supply wells that had ever been connected to a tank, tank truck, reserve pit, or production pit;
2. Analyze each of these water supply wells for benzene, toluene, ethylbenzene and total xylenes (BTEX), diesel-range organics (TPH-DRO), and gasoline-range organics (TPH-GRO) according to EPA Method 8015;
3. Eliminate back-siphoning potential; and,
4. Provide results to DEQ by January 1, 2007.

Geomatrix obtained petroleum hydrocarbon data from the Operators and incorporated them into the project database (**Appendix F**). **Appendix C** contains summaries of BTEX, TPH-DRO and TPH-GRO data.

7.4 Comparison to Applicable Standards

Water quality standards applicable to this project are USEPA maximum contaminant levels (MCLs) for drinking water, or those established in Chapters 8 and 17 of Wyoming DEQ Water Quality Rules and Regulations. Chapter 8 classifies groundwater according to use, and establishes standards based on classification primarily for non-hazardous substances. Classifications are as follows:

- Class I groundwater – Suitable for domestic use.
- Class II groundwater – Suitable for agricultural use.
- Class III groundwater – Suitable for livestock use.
- Class IV groundwater – Suitable for industrial use.
  - Class IV (A) groundwater has a total dissolved solids concentration <10,000 mg/L.
  - Class IV (B) groundwater has a total dissolved solids concentration >10,000 mg/L.
- Class V groundwater – Groundwater found closely associated with commercial deposits of hydrocarbons and/or other minerals, or which is considered a geothermal resource, is Class V (Hydrocarbon Commercial), Class V (Mineral Commercial) or Class V (Geothermal) groundwater.
- Class VI groundwater of the State may be unusable or unsuitable for use:
  - Due to an excessive concentration of total dissolved solids or specific constituents;
  - Is so contaminated that it would be economically or technologically impractical to make the water useable; or
  - Is located in such a way, including depth below the surface, so as to make its use economically and technologically impractical.

Geomatrix screened inorganic water quality data in the project database (**Appendix F**) against these standards (**Table 5**). **Appendix C** contains additional data summaries and detailed comparisons to applicable standards. Water quality standards for parameters not included in **Table 5** below were not exceeded in samples from any well.

Table 5 Summary of Water Quality Screening Results for Inorganic Parameters

Parameter	Well Type	Number of Sites Sampled	Number of Instances Parameter Concentration Exceeded Indicated Standard		
			Class I	Class II	Class III
Chloride	Domestic	50	0	0	0
	Industrial	167	0	20	0
	Stock	22	0	0	0
Fluoride	Domestic	50	5	NA	NA
	Industrial	167	64	NA	NA
	Stock	22	1	NA	NA
Sulfate	Domestic	50	7	1	0
	Industrial	167	27	13	0
	Stock	22	8	3	0
Sodium Adsorption Ratio	Domestic	50	NA	25	NA
	Industrial	167	NA	153	NA
	Stock	22	NA	16	NA

Notes:
NA - not applicable

Note: The water quality data set for inorganic parameters is limited to available SCCD data through June 2007.

Parameters that exceed applicable standards in **Table 5** do not imply impacts associated with oil and gas exploration and production. Rather, there is a tendency for fluoride, sulfate, and chloride concentrations in groundwater, among other parameters, to increase with well depth in the formation regardless of well type in the PAPA. Since industrial wells are generally completed deeper than domestic or stock wells, TDS concentrations tend to be higher in these wells. High sodium adsorption ratios appear to be a ubiquitous groundwater quality condition across the study area. A more detailed discussion of water quality trends in the study area is presented below in **Section 7.5**.

Petroleum hydrocarbon compounds were detected in 73 industrial wells sampled between the fall of 2006 and December 2007. Analytical results are summarized in summary **Table C-1** in **Appendix C**, and exceedences of applicable standards are highlighted where they occur. Petroleum compounds that were detected in wells include:

- Benzene in samples from 13 wells;
- Toluene in 37 wells;
- Ethylbenzene in seven wells;
- Xylenes in 12 wells;
- Total petroleum hydrocarbons in the gasoline range (TPH-GRO) in 16 wells;
- Total petroleum hydrocarbons in the diesel range (TPH-DRO) in 42 wells; and,
- Total petroleum hydrocarbons (TPH) by EPA Method 1664 in five wells.

Figure 17 shows locations of wells that exceeded petroleum hydrocarbon standards including:

- Benzene in samples from wells AM1140, AM1182, AM1187, AM1188, AM1237, AM1285, and AM1149. Analytical results from the latest sampling events however, indicate the concentration of benzene exceeded the standard in only wells AM1237, AM1182, and AM1149.
- Toluene, ethylbenzene, and xylenes in a sample from AM1140. These constituents have not exceeded their respective standards since the initial sampling on September 7, 2006. Toluene

and ethylbenzene were not detected in samples from the last three monitoring events conducted in February, July, and November 2007. Xylenes were present in one sample (July 16, 2007) at a concentration of 0.00160 mg/L, which is several orders of magnitude lower than the 10 mg/L standard.

- TPH-DRO in samples from wells AMI078, AMI147, AMI186, AMI160, AMI166, AMI190, AMI252, and AMI280. Results from the latest sampling events indicate TPH-DRO only exceeds the standard in samples from wells AMI186 and AMI252.

A key cause for the petroleum hydrocarbon detections, including benzene, in at least four industrial water supply wells is associated with tank backflow into wells (see Section 7.3 and **Appendix G**). Operators are working to determine the cause (source) of the low level petroleum hydrocarbons detected in other well samples including:

- Investigating characteristics of pipe dope compounds used during water well pump installation;
- Evaluating industrial water well drilling methods and techniques; and,
- Investigating potential natural sources.

Operators are also developing and implementing several Best Management Practices that include requiring:

- Only hydrocarbon-free pipe dope for industrial water well drilling and pump setting activities;
- Pumps, rods, and drop tube (discharge pipes) are free of grease and other hydrocarbons before installing in water wells; and,
- Backflow prevention devices and air gaps on all piping that connects tanks and water wells.

7.5 General Chemistry

Table 6 summarizes statistics for general groundwater chemistry grouped by wells with bottom elevations either greater than or less than 6900 feet amsl based on SCCD's 2006 data. Average TDS, sodium, chloride, fluoride, and sulfate concentrations tend to be higher in deep wells relative to concentrations in shallow wells. Calcium, potassium, and magnesium are generally higher in shallow wells than deep wells. Alkalinity concentrations do not indicate a correlation with depth.

Table 6 Water Quality Statistics - General Chemistry

Constituent	TDS	Alkalinity - $CaCO_3$	Ca	K	Mg	Na	Cl	F	SO4
Deep Wells (Bottom Elevations <6900 ft)									
Maximum	2670	332	70	3.9	16	865	207	12	1540
Minimum	178	72	0.6	ND	ND	16.9	ND	ND	1.0
Standard Deviation	452	49	14	0.8	2.4	135	33	2.7	316
Median	359	185	1.4	0.5	ND	137	15	2.0	84
Average	509	191	7.4	0.6	0.7	180	29	3.2	189.4
Shallow Wells (Bottom Elevations >6900 ft)									
Maximum	1000	326	110	24	29	327	30	3.6	684
Minimum	140	86	1.0	ND	ND	7.4	ND	ND	6.0
Standard Deviation	158	46	28	3.6	6.8	69	6.2	0.9	125
Median	226	180	28	1.5	4.5	43	2.0	0.2	12
Average	271	187	33	1.9	6.5	66	3.7	0.6	52

Figures D1 through **D9** in **Appendix D** are plots of TDS, alkalinity, fluoride, and major cations and anions concentrations relative to well bottom elevation. These figures illustrate that wells are more likely to contain relatively high or low concentrations of sodium, sulfate, fluoride, total dissolved solids, alkalinity, chloride, magnesium, calcium, and potassium based on their bottom completion depths. Key trends are summarized below:

- Sodium concentrations are high in deep wells relative to shallow wells. Sodium concentrations in deep wells are greater than 100 mg/L, while the majority of shallower wells have concentrations less than 100 mg/L.
- Deep wells are more likely than shallow wells to contain elevated concentrations of TDS, sulfate, chloride, and fluoride.
- Potassium, magnesium, and calcium concentrations tend to be higher in shallow wells relative to deep wells.
- Alkalinity concentrations do not indicate a correlation with depth.

These observations are consistent with those of previous studies (Glover, 1998; Martin, 1996; Chafin and Kimball, 1992) and with what would be expected due to the general tendency of deeper wells to intercept water that has had a longer residence time in the groundwater system. Consequently, more dissolved aquifer material has accumulated, and ion exchange reactions that tend to decrease concentrations of calcium and magnesium and increase concentrations of sodium and chloride have proceeded further.

Geomatrix plotted selected ionic chemistry data for PAPA wells on trilinear diagrams (e.g. Piper diagrams) to assess water quality characteristics. **Figure D10** (**Appendix D**) is a Piper diagram illustrating 2006 general ionic chemistry data for domestic wells within the PAPA and for the New Fork and Green Rivers. Dominant cations (positively charged ions) in domestic wells are calcium and sodium. Dominant anions (negatively charged ions) are bicarbonate and sulfate. These data plot on a linear trend between these cation and anion pairs, indicating three dominant water types: sodium bicarbonate, calcium bicarbonate, and sodium sulfate. Calcium bicarbonate tends to be the dominant water type in surface water and relatively shallow wells located in the northern part of the PAPA near the Town of Pinedale. Sodium bicarbonate is the dominant water type in deeper wells located in this same area. Domestic wells with sodium sulfate-type water are either relatively deep wells located near the Town of Pinedale, or are located adjacent to the New Fork River in the central part of the PAPA.

Piper diagrams for stock and industrial wells are shown on **Figures D11** and **D12** in **Appendix D**. Stock wells displaying calcium bicarbonate-type are located in the northern portion of PAPA. Of the 22 stock wells sampled, only two exhibit sodium bicarbonate-type water and are located in the north PAPA (AS054) and on The Mesa (AS036). The remaining stock wells are either sodium sulfate-type (seven wells) or are intermediate between sodium sulfate-type and sodium bicarbonate-type.

Figure 18 shows locations of industrial wells where the percent concentrations of dominant cations and anions are >70 percent milliequivalents per liter (meq/L) (i.e. where one of the water types indicated above is clearly dominant). The figure also shows the water type of samples from the New Fork and Green Rivers. Groundwater from the majority of industrial wells is sodium bicarbonate-type, sodium sulfate-type, sodium chloride-type, or a transition between these three types. Only industrial well AMI061, a shallow well (15 ft deep) located in the north PAPA, has calcium as its dominant cation. Bicarbonate is the dominant anion in approximately 53 percent of industrial wells, followed by sulfate (27 percent), and chloride (7 percent). Groundwater from the remaining industrial wells does not display a dominant water type.

Based on the above analyses, the following summarizes general groundwater chemistry for industrial wells completed in the Regional Wasatch Formation HSU:

- Sodium bicarbonate is the dominant groundwater type in industrial wells located north of the New Fork River. Approximately 68 percent of industrial wells with the strongest sodium bicarbonate signatures (>70 percent meq/L for both sodium and bicarbonate) are located north of the New Fork River. A few industrial wells yield water with strong sodium sulfate-type groundwater are located north of the New Fork River; however, the general tendency is toward sodium bicarbonate-type chemistry.
- Groundwater in industrial wells located along the New Fork River corridor in the central PAPA is primarily sodium bicarbonate-type.
- The majority (approximately 90 percent) of industrial wells with chemical signatures that are strongly sodium sulfate-type are located south of the New Fork River. Only two wells with this signature are located north of the river.
- Industrial wells with sodium chloride-type signatures are located south of the New Fork River in an east-west oriented area extending from T 30 N, R 108 W, Section 10 to T 30 N, R 109 W, Section 25. This orientation may be related to the distribution of a rock type that contains chloride minerals (e.g. halite).

Geochemical data available for the PAPA is consistent with groundwater recharge primarily from the north and east with groundwater movement generally to the south and west. Shallow groundwater chemistry in the northern end of the PAPA is characterized by calcium carbonate. The ionic signature similarity between water in the New Fork River and shallow wells west and south of the Town of Pinedale may indicate the river is recharging groundwater in the northern part of the PAPA. Chafin and Kimball (1992) indicate that in relatively short distances from recharge areas sodium bicarbonate becomes the dominant water type through cation exchange of calcium and magnesium for sodium. This is consistent with sodium bicarbonate observed to be the dominant water type in deeper wells in the Town of Pinedale area and throughout the PAPA north of the New Fork River. Groundwater in the southern portion of the PAPA is located farther from its recharge area adjacent to the Wind River Range. Longer residence time and possibly contact with different mineral assemblages results in sulfate- and chloride-rich groundwater. USGS well 31-107-23dc (**Figure 16**), located east of the southern PAPA, is calcium sulfate-type, indicating a source of sulfur hydraulically upgradient from this area.

8.0 CONCEPTUAL MODEL

This section describes Geomatrix's current understanding of the groundwater system within and around the PAPA. It is based on a synthesis of existing lithologic, hydrologic, climatological, and water quality data. **Figure 19** presents a conceptual model of the groundwater system oriented approximately northwest to southeast, generally along the axis of the Pinedale Anticline. Conceptually, the diagram identifies hydrostratigraphic units, groundwater flow paths, and shows depths and typical completions for the various wells in the PAPA.

The PAPA is located in a northwest to southeast oriented valley between the Wind River and Wyoming mountain ranges. The valley is characterized by a semi-arid landscape, rocky soil, and sparse vegetation, with numerous ephemeral drainages dissecting ridges and buttes. Topographic elevations range from approximately 6850 feet to over 7700 feet amsl on top The Mesa in the north-central portion of the PAPA. The New Fork River and Green River are the major hydrologic features and, in the northern half of the PAPA, generally serve as the northern, eastern and western boundaries. No other significant perennial streams are located within the PAPA. Several springs occur along the slopes of topographic features within the PAPA.

Precipitation at the Town of Pinedale, located adjacent to the north PAPA boundary, averages approximately 10.82 inches per year. In the nearby mountains, precipitation averages between 20 and 24 inches annually. Precipitation data for the Pinedale area indicate below normal precipitation for four the six years between 2001 and 2006. Based on climatological data from the Town of Pinedale, average annual evaporation potential may be as much as four times higher than average annual precipitation.

Groundwater occurs in three principal HSUs within the PAPA: River Alluvium HSU, Shallow Wasatch Formation HSU, and Regional Wasatch Formation HSU. The River Alluvium HSU occurs adjacent to the New Fork River, the East Fork River, the Green River, and each of their tributaries. The River Alluvium HSU is generally comprised of sand and gravel, is up to 80 feet thick, and is up to two miles wide in places. Groundwater most likely occurs under water table conditions near land surface within alluvium and is hydraulically connected to both rivers and streams and to the underlying Wasatch Formation. This unit is expected to have high permeability relative to bedrock HSUs.

The Wasatch Formation is comprised of discontinuous beds of sandstone, siltstone, and mudstone/shale and is generally close to or at land surface over much of the PAPA. On The Mesa, Wasatch Formation bedrock is covered by up to 35 feet of terrace gravels. Generally in the PAPA, the Shallow Wasatch Formation HSU is present above the Green River and New Fork River valleys. Groundwater in the Shallow Wasatch Formation HSU occurs in discontinuous sandstone units/lenses within finer-grained siltstone or mudstone/shale units. Based on information from well driller's logs, this HSU does not appear to be continuously saturated. Groundwater in the Shallow Wasatch Formation HSU is expected to migrate vertically to the Regional Wasatch Formation HSU, while a portion travels laterally on top of siltstones/mudstones and discharges along the slopes of topographic features in the form of springs and seeps. Depth to groundwater in the Wasatch Formation varies based on topography and well depth. Along the New Fork River, many wells completed in the Regional Wasatch Formation HSU are artesian, while depth to groundwater on The Mesa is over 500 feet in the Regional Wasatch Formation HSU.

Geochemical data available for the PAPA is consistent with groundwater recharge to the PAPA primarily from the north and east with groundwater movement generally to the south and west. Similarities between water in the New Fork River and shallow wells west and south of the Town of Pinedale may indicate the river is recharging groundwater in the northern part of the PAPA. Sodium bicarbonate becomes the dominant water type in the north PAPA, increasing with depth and distance from recharge areas as ion exchange reactions remove calcium and magnesium from groundwater and replace them with sodium. Sulfate- and chloride-rich groundwater occur in the southern portion of the PAPA due to longer residence times and possibly contact with different mineral assemblages, which is located farther from its recharge area adjacent to the Wind River Range.

Groundwater in the Regional Wasatch Formation HSU may best be characterized as semi-confined due to the discontinuous nature of the water-bearing sandstone units both vertically and horizontally. Groundwater flows through the aquifer in sandstone units and along joints and fractures in sandstones, mudstones, and siltstones. The heterogeneous nature of the aquifer indicates that groundwater probably flows along tortuous paths from recharge areas to discharge areas. The majority of recharge occurs outside the PAPA adjacent to mountain ranges located to the northeast, north and west. Some recharge also appears to originate from the New Fork and Green Rivers in the northern portion of the PAPA. Annual recharge within the PAPA boundaries is estimated to be between 0 and 0.5 inches. The Mesa, possibly due to its topographic elevation, may receive more recharge (on the order of 2.8 inches according to **Figure 13**) than lower elevation portions of the PAPA. Other possible sources of groundwater recharge include leakage from irrigation ditches located on the north side of the New Fork River and from excess water irrigated to crops from the ditches.

The overall pattern of groundwater flow is from northeast to southwest away from primary recharge areas adjacent to the Wind River Range. Groundwater is somewhat mounded under The Mesa forming a groundwater ridge. This indicates that recharge originating from the north and/or from precipitation on the high Mesa may be occurring. In the southern portions of the PAPA, south of the New Fork River, a groundwater ridge is present beneath Ross Ridge and Blue Rim, topographic highs that may be areas of secondary groundwater recharge.

The New Fork, East Fork, and Green Rivers exert considerable influence on groundwater flow in the northern and central portions of the PAPA. Particularly in the central portion of the PAPA, groundwater from the Regional Wasatch Formation HSU discharges to the New Fork River (**Figure 19**). Upward-directed vertical gradients are present in the Regional Wasatch Formation HSU proximal to the lower New Fork River. Numerous flowing wells are located adjacent to the New Fork River between the mouth of the East Fork River and the confluence with the Green River indicating an upward vertical potential. Groundwater exchange with rivers probably occurs through alluvial material except where bedrock is exposed in the river channels. Available flow data for the New Fork River, East Fork River, and Boulder Creek indicate the New Fork River gains flow from groundwater during base flow conditions. In the southern PAPA, groundwater flow appears to roughly parallel to the New Fork and Green Rivers except in close proximity to the New Fork River.

9.0 MONITORING PROGRAM EVALUATION

The current PAPA monitoring program was designed to fulfill the requirements of the 2000 ROD (BLM 2000a). Based on our review of the monitoring program that has been implemented by the SCCD on behalf of the Operators since 2001, the following have been accomplished:

- All known domestic and stock wells within one mile of existing and proposed oil and gas activity were surveyed.
- One round of data (e.g., water level, general chemistry, and petroleum hydrocarbons) from each well identified by the survey was obtained.
- All industrial water supply wells, as well as domestic wells and stock wells located within one mile of a gas production well are monitored annually for static water level and general chemistry.
- New industrial and domestic water supply wells are inventoried on an annual basis. New industrial wells and new domestic wells located within one mile of active gas production wells are monitored for static water level and general chemistry. Additionally, new wells are initially sampled for BTEX and TPH.
- Ten percent of existing industrial wells are sampled for BTEX and TPH on an annual basis.
- All well identification data, water levels, field water quality measurements, and analytical data are incorporated into a database.

In 2005, DEQ raised their concerns with the current monitoring program to the BLM. DEQ (2005) stated that although the current approach to groundwater monitoring meets the requirements of the language in the ROD, it "…does not provide a reliable, scientific method of determining whether oil and gas activities have impacted either water quantity or quality of any of the aquifers located within the Pinedale Anticline area." They further state that because it is not known which aquifers wells are completed in, it is not possible to evaluate whether oil and gas activities are impacting groundwater resources.

The adequacy of the monitoring program can be judged based on its ability to: 1) produce data sufficient to describe hydrogeologic conditions, and 2) detect potential groundwater impacts due to natural gas development. While the monitoring program has produced data sufficient to adequately describe baseline conditions with regard to natural water quality, Geomatrix identified several deficiencies in the program as outlined below:

- The potentiometric map presented in this report is based on a mix of groundwater elevation data obtained at various times of year over a six-year period. Because of this methodology used to collect water level data, it is not known how much seasonal variations effect groundwater flow direction.

- Temporal trends in potentiometric head are difficult to discern due to infrequent (annual) water level data collection. Because water levels are measured once annually, it is not possible to discern potential effects of long term water level decline that might be indicative of over-pumping from those of natural cyclical short term (seasonal) water level changes. Furthermore, seasonal changes in groundwater flow patterns (if any) cannot be determined.

- Groundwater and surface water interaction/exchange cannot be quantified, and groundwater discharge to surface water cannot be adequately calculated with existing data. Existing surface water flow data are not adequate to accurately measure increases/decreases in flow that might indicate the influent or effluent character of rivers and streams. There are no monitored wells completed in river alluvium that would allow comparison of groundwater and surface water hydrographs.

- There are numerous discrepancies or irregularities in water well location and elevation data in the project database. Although elevations were calculated for each monitoring point using USGS DEM data for this report, this method is highly dependent on accurate horizontal wells coordinates. There are several instances in the database where coordinates for the same well obtained from different sources are significantly different. In some cases the difference is greater than a mile.

- The ability to detect water quality changes due to spills or excursions from natural gas wells is dependent on a number of factors, including the horizontal and vertical location of the monitoring well with respect to a source of potential impacts, groundwater flow direction, and vertical/horizontal permeability contrasts of the aquifer. The vast majority of industrial wells are perforated hundreds of feet below the first water bearing zone, and thousands of feet above the gas-producing zones of any nearby natural gas wells. There is no information regarding vertical permeability of the Wasatch Formation within the PAPA, which in sedimentary aquifers are typically low relative to horizontal permeability. Although secondary permeability features such as fractures, cracks, and joints can enhance vertical permeability, industrial supply wells are more likely to detect impacts from sources that are relatively close and located in the same vertical zone as the well's perforated interval. Stock wells are typically completed in the Shallow Wasatch Formation HSU, and are therefore more likely to detect impacts from surface spills if they are located hydraulically downgradient from a spill.

- The monitoring program should be able to detect water quality changes due to inter-aquifer leakage induced by pumping or exchange between different water bearing intervals connected by multiple perforated intervals within a particular well. There is a general tendency toward increased dissolved solids with depth; however, the trend is not universal. Because of the variable water quality between individual sandstone lenses in the Wasatch aquifer, inter-aquifer leakage or exchange through the well may be evidenced by changes (increase or decrease) in water quality over time at a particular well.

The Revised DSEIS (BLM 2007) indicates that a new, scientifically-based water resources monitoring plan will be developed jointly by DEQ and BLM within six months of issuing the ROD. The Revised DSEIS states that the monitoring plan will be developed in accordance with the BLM's Regional Framework for Water Resources Monitoring to Energy Exploration and Development (USGS 2007b) guidance document, and that "…Operators will be consulted for additional operational perspective in devising a feasible monitoring plan and funding its implementation."

10.0 DATA GAPS

While evaluating the existing groundwater dataset for the PAPA, Geomatrix identified several data gaps that result in uncertainty to interpretations and analyses presented in this report. Each data gap was assigned a number, and its basis is explained in **Table 7**.

Table 7 Summary of Data Gaps

Data Gap	Description and Basis
1	There is a lack of contemporaneous groundwater and surface water elevation data for the PAPA. Currently, water level data are collected over the course of a field season and the existing dataset contains seasonal effects that may affect groundwater flow interpretation, especially at the more localized level.
2	There is insufficient surface water flow data to determine influent/effluent characteristics of rivers. There are no available synoptic flow data, and flow data collected from essential USGS gaging stations do not have overlapping periods of record.
3	There is insufficient data to determine groundwater/surface water interconnection. No monitoring wells are completed in the Alluvium HSU. Water level data collection is too infrequent to discern the response (if any) of the Regional Wasatch Formation HSU to changes in New Fork River stage.
4	There is insufficient aquifer hydraulic property data (hydraulic conductivity, storativity) to determine potential groundwater discharge rates to rivers and groundwater velocity/travel time in the various HSUs.
5	Water level monitoring is too infrequent to detect potential water level decline. Seasonal water level fluctuations cannot be discerned from annual water level measurements and more frequent measurements are necessary to create groundwater hydrographs for the various HSUs. Also, potential changes in hydrostatic pressure are not being monitored in artesian wells near the New Fork River.
6	Mesa and Antelope Springs have not been characterized for flow and water quality. These springs likely issue from saturated zones within the Shallow Wasatch Formation HSU and would be expected to be sensitive to short-term variations in precipitation. Their flow and water quality characteristics should be documented to augment the baseline data set.
7	The hydraulic connection between the Shallow and Regional Wasatch Formation HSUs has not been investigated. Current interpretations are based on information contained on well driller's logs, which can be inconsistent.
8	Confidence in well reference elevation data is low due to the types of instrumentation used to collect data. Accurate positional and reference elevation data is crucial to obtain accurate hydrogeologic interpretations.

11.0 RECOMMENDATIONS FOR FUTURE MONITORING

In addition to addressing existing data gaps described above in **Section 10**, Geomatrix recommends changes to the current monitoring program in order to optimize its ability to detect and quantify water resource impacts, as well as increase its efficiency and cost effectiveness. Water quality data generated by the current monitoring program adequately describes baseline conditions in the Shallow Wasatch and Regional Wasatch Formation HSUs, as well as in the New Fork River. Future monitoring efforts should focus on detecting changes in water quality and water quantity. Based on a review of available information and data, Geomatrix proposes the following modifications to the existing monitoring program.

Water Quantity

- Survey all existing and new wells to a common horizontal and vertical datum by a licensed professional land surveyor.
- Measure water levels on a frequent basis in a subset of domestic, stock, and industrial water wells. Non-pumping wells located both north and south of the New Fork River should be selected for the program, if present.
- Measure water levels in domestic, stock, and industrial wells from which samples will be collected (see below) during a compressed timeframe (1-2 weeks) at a consistent time of each year (e.g. August or September).
- Water level data should be examined for trends on an annual basis. Any perceived declining trend should be investigated to determine the cause.
- Compile water usage data for each water supply well within the PAPA on an annual basis.

Groundwater/Surface Water Interaction

To describe the interconnection between the New Fork and Green Rivers, Alluvium HSU, and Regional Wasatch Formation HSU, river stage and groundwater levels in each HSU should be measured on a frequent schedule. Since none currently exist, monitoring wells would need to be installed in alluvial aquifers adjacent to these rivers. Data collection should be coordinated with USGS activities at existing stream gaging stations to facilitate comparison of the data sets.

Water Quality

- Inorganic constituents pH, TDS, sulfate, chloride, fluoride, and SAR have been measured at concentrations in excess of Class I and/or II groundwater standards. Elevated fluoride and SAR concentrations appear to be ubiquitous conditions in the PAPA and probably do not warrant continued inclusion in the monitoring program. Sulfate and chloride appear to be positively correlated with TDS. Since monitoring conducted to date adequately describes baseline water quality conditions within the PAPA (excluding alluvial aquifers and springs), future monitoring of inorganic parameters should be limited to field measurements of pH, temperature, specific conductance, and TDS.

- Three groups of wells, each comprised of one third of all domestic, stock, and industrial wells, should be monitored on a rotating annual basis for static water level, pH, T, SC, and TDS. Wells should be selected so that each of the three groupings represents, to the extent possible, an even areal distribution over the PAPA and the various HSU. Concentration trends should be examined and appropriate action taken to investigate any perceived degradation of water quality.

- Coordinate the timing of New Fork River monitoring station with groundwater monitoring activities.

- All industrial wells with petroleum concentrations that exceed applicable standards should be sampled on a quarterly basis (or on a schedule that is appropriate based on risk and frequency of use) until the source(s) of petroleum hydrocarbons are determined and appropriate action taken in accordance with federal and state regulations.

- All new domestic, stock, and industrial wells that meet the 2000 ROD requirements should be initially sampled for all parameters in the current SAP (SCCD 2007), then incorporated into the modified monitoring program.

- All future analyses for petroleum hydrocarbons (TPH-DRO, TPH-GRO, BTEX) should be conducted using appropriate analytical methods (e.g. EPA Method 8015/8020).

- Protocols should be established for collecting representative volatile petroleum hydrocarbon samples (e.g. BTEX, TPH-GRO) from industrial and stock wells. Current methods include use of submersible electric pumps to collect these samples, which may result in losses of volatile compounds and results that are not representative of groundwater concentrations. Electric submersible pumps may be used to purge wells, but they should not be used for collection of volatile petroleum hydrocarbon samples. Appropriate sample collection equipment includes positive displacement pumps (e.g. pneumatic bladder or piston pumps), discreet interval samplers (e.g. thief sampler), or bailers. Care must be taken not to agitate the samples during collection or transfer to sample containers. Samples from domestic wells should continue to be collected using the existing pumping system in order to maintain the integrity of sanitary well seals. If petroleum hydrocarbons are detected in domestic wells, the need to resample using other procedures should be assessed.

- Implement Best Management Practices that require: hydrocarbon-free pipe dope in water well applications; cleaning all down-hole equipment before installing in water wells; and, backflow prevention devices and air gaps on all piping that connects tanks and water wells.

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