PHASE I HYDROGEOLOGIC CHARACTERIZATION OF THE MAMM CREEK FIELD AREA IN GARFIELD COUNTY

Prepared for
Board of County Commissioners
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URS

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Appendix

Appendix A GPS Waypoint Data for Measured Sections

Analyte	Any chemical or radionuclide whose concentration or activity in a water sample is analyzed by an analytical laboratory.
Anoxic	An anoxic water lacks measurable DO.
BTEX	Acronym for the organic compounds: benzene, toluene, ethylbenzene, and xylene isomers.
CAS	Chemical Abstracts Service assigns a unique number to identify analytes that may have multiple chemical names. The registry number is called a “CAS Number.”
CDNR	Colorado Department of Natural Resources.
CDPHE	Colorado Department of Public Health and Environment.
COC	Contaminant of Concern
COGCC	Colorado Oil and Gas Conservation Commission is a division of the CDNR that oversees oil and gas exploration in Colorado.
CWQCC	Colorado Water Quality Control Commission is a division of CDPHE that sets standards for groundwater and surface water quality in Colorado.
DO	The concentration of dissolved oxygen in a water sample.
DQA	Data quality assessment.
DQOs	Data quality objectives.
EPA	United States Environmental Protection Agency.
Geochemical Indicator	These are analytical parameters, or combinations of parameters, which indicate a geochemical environment, or condition of interest.
gpm	Gallons per minute
gpm/ft	Gallons per minute per foot of drawdown (specific capacity)
Hardness	One definition of “hardness” is the concentration of dissolved metals in water that can react with sodium-soaps to precipitate an insoluble residue (Drever 1988). A chemical definition of hardness is given later in the text.
HCO_3	Bicarbonate ion, HCO_3^-
MCLs	Maximum Contaminant Levels in drinking water are concentration limits set by EPA.
meq	Milliequivalents of an aqueous ion.
meq/L	A concentration unit in meq per liter of water.
mg	An mg is one milligram, or one thousandth of a gram.
mg/L	A concentration unit in milligrams per liter of water. A concentration of 1 mg/L is approximately equal to 1 PPM.

MSDS	Material Safety Data Sheet.
Oxidant	An oxidant or “oxidizing agent” is a chemical which gains electrons during a redox reaction, and becomes “reduced” in the process. Oxygen is a strong oxidizing agent in its reaction with hydrogen to form water.
PCA	Principal components analysis, a multivariate statistical method.
pH	pH describes the acidity of a water sample. pH values near 7 are considered “neutral”, while lower pHs (e.g. 4) are “acidic”, and higher pHs (e.g. 10) are “basic”. Most unpolluted natural waters have pH values between 6 and 9. Technically, pH is the negative log of the hydrogen ion activity in a water sample.
PPB	Parts per billion, a concentration unit similar to μg/L.
PPM	Parts per million, a concentration unit similar to mg/L.
QA/QC	Quality Assurance and Quality Control.
Redox	Redox reactions are chemical reactions which involve electron transfer, and the processes of oxidation and reduction.
Reductant	A reductant or “reducing agent” is a chemical which loses electrons during a redox reaction, and becomes “oxidized” in the process. Hydrogen is a good reducing agent in its reaction with oxygen to form water.
SAR	Sodium adsorption ratio.
SLC	SLC is a “standardized linear combination” of the original variables in PCA. PCA finds the set of SLCs, which together account for the variance of the original dataset.
SOP	Standard Operating Procedure.
SOW	Scope of work.
SO4	Sulfate ion, SO_4^{2-}
Stable Isotope	A non-radioactive isotope of an element.
Surrogate (SUR)	In analytical chemistry, surrogate compounds are manmade chemicals added to a sample for quality control purposes. Surrogates are exotic chemicals presumed to be absent from samples of environmental media.
TDS	Total Dissolved Solids.
TPH	Total Petroleum Hydrocarbons
TSS	Total Suspended Solids.
ug	A microgram is one millionth of a gram. This unit is sometimes printed as μg.

µg/L	A concentration unit in micrograms per liter. A concentration of 1 µg/L is similar to 1 PPB.
USGS	United States Geological Survey.
Water Quality Data	Chemical analyses of samples of surface water or groundwater.
Water-Type	The major dissolved cations and anions in a groundwater or surface water may be identified through chemical analysis, and their relative abundances define a "water-type" used to describe the water. If, for example, sodium is the most abundant cation and chloride is the most abundant anion in meq units, the analyses indicate a Na-Cl water-type.

URS completed the Phase I Hydrogeologic Characterization under contract with the Garfield County Board of County Commissioners. The project area is approximately 110 square miles in size and is located south of the cities of Rifle and Silt in western Colorado. The scope of work for the hydrogeologic characterization was developed by Garfield County, the Colorado Oil and Gas Conservation Commission (COGCC), the Grand Valley Citizens Alliance, and the Western Colorado Congress. The primary objectives of the study are to address vulnerability of surface water and groundwater resources in the area to impacts from gas well development and other human activities, and to evaluate if a relationship exists between water quality variations and lithology type (i.e. sandstone, mudstone, or alluvium).

The study area comprises the majority of the Mamm Creek gas field in the southeastern portion of the Piceance Basin. The study area is defined as the area south of the Colorado River in four townships: townships 6 and 7 south (6S, 7S) and ranges 92 and 93 west (92W, 93W). Within the study area, the ground surface ranges from an elevation of 9,400 feet above mean sea level (ft MSL) in the southwest corner above West Mamm Creek (on the northeast flank of Battlement Mesa), to a low of 5,280 ft MSL along the Colorado River in the northwest corner near the town of Rifle.

The stream drainages and gulches in the study area include, from west to east, Beaver Creek (very small portion), Helmer Gulch, Ramsey Gulch, Dry Creek, West Mamm Creek, Gant Gulch, Middle Mamm Creek, East Mamm Creek, Mamm Creek, Dry Hollow Creek, Alkali Creek, West Divide Creek, East Divide Creek, and Divide Creek.

The Phase I study involved the compilation and evaluation of existing data, with a limited amount of field work. Phase I represents a “broad brush” view of the overall area. Based on the data integration and evaluation completed in Phase I, recommendations for Phase II activities are proposed at the end of this report. Because the study encompasses a 110 square mile area with the objective of identifying impacted versus unimpacted or vulnerable areas, the focus was not to evaluate all of the data collected in association with studies of the Amos/Walker and Dietrich water wells, or the West Divide Creek Seep area. These areas have been studied in detail to evaluate the relationship between gas well drilling and completion activities and the occurrence of thermogenic methane in water wells or West Divide Creek.

Existing data used in this study included an electronic database obtained from the Colorado State Engineers Office (SEO) containing over 6,000 records and “receipts” for approximately 495 permitted water wells. Water well driller logs were extracted from the database, reviewed, and lithologic and aquifer testing data were entered into a separate database table.

Gas well data was obtained in an electronic database format from the COGCC and included thousands of records in over 20 data tables for approximately 978 gas wells drilled in the study area. COGCC maintains an on line database with additional information obtained from scanned paper documents. However, electronic copies of portions of this database are not available at this time. The on line database and GIS system were utilized repeatedly to verify information and to fill in data gaps in the Access database. Gas well data was also obtained from EnCana and Bill Barrett Corporation (BBC) in the form of Petra database files. These data were used to construct regional cross-sections and an isopach map of the Wasatch Formation thickness. Gas well bradenhead pressure data collected during 2004 and 2005 was provided to URS by the COGCC.

Water quality results were also obtained from the COGCC in an electronic Access database format. Water quality data were available for over 3,000 unique samples with more than 70,000 individual analytical results. Samples were obtained from more than 500 locations including domestic, irrigation, monitoring, air sparge and water supply wells, and cisterns, springs, streams, seeps and ponds. Much of these data were provided to COGCC for this study, and represents baseline water quality samples collected by EnCana and BBC.

Each of the three primary databases (water wells, gas wells, and water quality) were linked separately to GIS mapping software, ArcMap. Database queries were developed to extract select data for posting on basemaps as layers. Layers of data were arranged in various combinations to evaluate relationships between datasets (i.e., bradenhead pressures and geologic structure trends).

A large amount of data was reviewed and evaluated to form the basis of this report. The report is long. The top 10 key findings of this study are:

1. There is a laterally continuous stratigraphic sandstone interval in the middle of the Wasatch Formation beneath the east half of the study area. Otherwise, the Wasatch is dominated by mudstone lithologies, which account for upwards of 90 percent of the material.
2. The Wasatch Formation has been eroded by uplift of the Divide Creek Anticline, which is located in the southeast portion of the study area. The thickness of the Wasatch increases from about 1,200 feet in the southeast to almost 6,000 feet in the northwest portion of the study area.
3. A number of linear anomalies were identified within the study area. These linear anomalies are likely related to subsurface fracture zones. Shallow groundwater and deeper groundwater and formation waters may move preferentially within these zones.
4. The occurrence in groundwater of dissolved methane, selenium, fluoride, and higher TDS concentration sodium-chloride and sodium-sulfate water types is more common beneath the eastern half of the study area.
5. In terms of water well yields, alluvial aquifer wells have higher capacities than do wells completed in the Wasatch aquifer. Alluvial aquifer water quality is generally better than for the Wasatch aquifer (lower TDS concentrations).
6. Within the entire study area, water quality is generally better in water wells located on Grass Mesa (lower TDS, sodium, and chloride). The Wasatch aquifer is likely recharged from precipitation in this area. The Wasatch is thicker in this area so the water wells are higher above the top of gas in the Mesaverde, and there are fewer deep linear anomalies.
7. For the major cations and anions, concentrations generally decrease with water well depth for calcium, magnesium, and bicarbonate. Concentrations of sodium, sulfate, chloride, and TDS generally increase with water well depth.
8. Near Dry Hollow Creek (Section 3 7S 92W and Section 34 of 6S 92W), there is an area where Wasatch water wells are capable of above-average well yields for the area, the sodium-sulfate water type is most common, and sodium-chloride water types occur. URS interprets these factors to result from a zone of higher fracture density, which increases the ability for both shallow and deeper fluids to move horizontally and vertically in this area.
9. Both biogenic and thermogenic methane have been identified in water wells in the study area. Isotopic analyses and gas compositional data is used to distinguish the two origins

and requires methane concentrations greater than about 1 or 2 mg/L. Dissolved methane concentrations exceed 1 mg/L in 29 water well samples that have not been tested for isotopic and compositional elements.

10. On Hunter Mesa, which may have the densest occurrence of gas wells, there are few water wells or surface water samples to allow evaluation of water quality.

There are several water quality issues or anomalies observed from samples collected in the study area. With a few exceptions, the issues are primarily in the eastern half of the study area. In the western portion of the study area there is a reasonable amount of water quality data for the Grass Mesa area, but there are few water wells located on the central portion of Hunter Mesa, and therefore little water quality data is available for evaluation. In the eastern portion of the study area, elevated groundwater concentrations for fluoride, selenium, sulfate, nitrate, and methane were observed in a number of water wells. For all of these constituents except methane, the concentrations exceed groundwater and/or drinking water quality criteria established by the Colorado Water Quality Control Commission and the USEPA. There is no groundwater standard established for methane. There are also a number of water wells with a sodium-chloride or sodium-sulfate water type, generally in conjunction with a relatively high total dissolved solids (TDS) content. The elevated nitrate concentrations are most likely due to fertilizer applications entering shallow groundwater. The presence of elevated fluoride, selenium, sulfate, chloride most likely reflect increased flow or mixing of groundwater from deeper subsurface intervals with shallow groundwater supplies.

These deeper subsurface intervals could be represented by a portion of or the entire depth interval from the base of the deepest potable water supply well in the area (600 feet below ground surface) to the depth of the deepest structural elements (basement faults or fractures greater than 10,000 ft bgs). Existing water quality data is available for shallow water wells, and for produced water from gas wells completed to depths about 6,000 to 8,000 feet bgs. Unfortunately, there is no available water quality data from the deeper Wasatch Formation and uppermost Mesaverde Group in the study area, i.e. the interval between the potable water aquifer and the top of gas. This is the stratigraphic interval immediately beneath the potable bedrock aquifer, and is the most likely zone to mix with the potable water.

Although water quality data suggests mixing of deeper subsurface fluids with shallower potable water in the eastern half of the study area, the cause of this mixing is unknown for certain, and there may be more than one cause. The eastern half of the study area has two significant differences from the western half of the study area; the thickness of the Wasatch Formation overlying the top of gas is thinner in the eastern half (about 1,200 feet of rock) than the western half (about 6,000 feet of rock), and there is more evidence of historic subsurface structural activity (The Divide Creek anticline and linear anomalies) in the eastern half of the study area. The historic structural activity and linear anomalies are largely related to the presence of the Divide Creek anticline which is located beneath the east half of the study area. In short, the natural movement of deeper subsurface fluids is more likely to occur beneath the eastern half of the study area because of geologic structures associated with the Divide Creek anticline. The presence of completed gas wells could potentially provide a vertical conduit within the stratigraphic interval beneath the potable bedrock aquifer and underlying formations, including deeper productive gas reservoirs. Several recently drilled gas wells in this area have been tied directly to impacts on domestic water wells, where the impacts have been essentially coincident with drilling activity and remediation of the impacts has occurred.

Due to the absence of historic water quality data prior to drilling of gas wells to serve as a baseline in the area, the water quality issues observed in the study area could predate gas well drilling activities. We cannot make a definitive statement other than the water quality issues could be caused by natural conditions and/or potentially the presence of gas wells in the area.

Geology

The study area is located within the southeast portion of the Piceance Basin. The Piceance Basin is a large sedimentary basin and structural depression formed during the Laramide Orogeny, which occurred between the Late Cretaceous and Eocene time periods, approximately 70 to 40 million years ago. There are several northwest-trending anticlines in the southern portion of the basin, and one of these, the Divide Creek anticline, is located immediately southeast of the study area. The plunging nose of this anticline extends northwest into the study area. The presence of the Divide Creek anticline, and related regional structural features in this area, may impact the occurrence of natural gas in the subsurface.

This report focuses on bedrock units of the Mesaverde and Wasatch Formations, and unconsolidated alluvial sediments located in narrow belts immediately adjacent to stream channels. Wasatch outcrop is present at the ground surface for all but the southwest corner of the study area, where the overlying Green River Formation is present. The Wasatch is underlain by the Mesaverde Group. Gas wells drilled in the study area typically have total depths between 6,000 to 10,000 feet below ground surface, and are completed within the Williams Fork Formation or deeper sands within the Mesaverde Group.

The thickness of the Wasatch Formation ranges from about 1,200 feet on the Divide Creek anticline in the southeast corner of the study area, to over 5,600 feet along the west side of the study area. The deepest water wells are screened to a depth of 600 feet, so all of the bedrock water well completions are within the Wasatch Formation. Bedrock water well completions account for about 90 percent of all water wells, with the remainder completed in alluvial materials.

One of the few project tasks involving the collection of new data was the Wasatch sandstone outcrop study. This task was performed to evaluate the lateral continuity of individual sandstone units comprising the Wasatch Formation in the study area. This information was combined with water quality data to evaluate variations in water quality across the study area with respect to the regional occurrence of sandstone units.

URS geologists measured five outcrop sections located around the study area. Based on field observations, URS identified a laterally extensive sandstone unit located in the lower third of the Wasatch section within the study area. This unit consists of two sandstone intervals separated by over 500 feet of mudstone, and is termed the Molina-like sandstone unit in this report, for a general resemblance to the Molina Member type section described by Donnell (1969). The interpreted Molina-like interval in this area is approximately 1,000 feet thick, including the middle mudstone interval. The Molina-like sandstone unit outcrops in the east half of the study area. It is underlain by mudstones of the Atwell Gulch Member, and overlain by the Shire Member, a thick sequence consisting predominately of mudstones.

Measured sections ranged in thickness from 210 to 605 feet, and were generally measured in areas where the most sandstone is present. However, the Wasatch is composed primarily of mudstone. The percentage of sandstone intervals present at each section ranged from 19 (Mamm Creek) to 40 percent (Divide Creek). The maximum thickness of individual sandstone intervals ranged from 20 feet at Davis Point, to 75 feet at the Dry Hollow location. The maximum thickness of an individual mudstone unit in a measured section was 124 feet at the Mamm Creek location.

Eight sandstone and two mudstone lithofacies were characterized at each measured section. The sandstone lithofacies generally represent deposition in fluvial channel environments. Mudstone lithofacies represent deposition on an alluvial plain, as overbank deposits.

Three major structures traverse the study area, which include the Divide Creek anticline, Rifle-Grand Hogback syncline, and an unnamed syncline. The axis of the unnamed syncline is located west of Grass Mesa, and trends north-northwest to south-southeast. This syncline represents the structural depression between the Divide Creek anticline and the Rulison anticline to the west.

An independent aeromagnetic lineament analysis was not conducted for this study. However, data and lineaments interpreted in a previous study by Hoak and Klawitter (1997) were evaluated and further refined for this study. The aeromagnetic lineaments were digitized from regional maps into a GIS shapefile. The interpreted aeromagnetic lineaments are separated into three categories: shallow (short wavelength data), transitional (intermediate wavelength data), and basement (long wavelength data). A lineament analysis was performed by URS from aerial and satellite imagery. In the eastern half of the study area, the dominant lineament trends are oriented west-northwest to east-southeast and northeast to southwest. These trends are similar to the aeromagnetic anomalies. Lineaments in the southwest quadrant of the study area are oriented closer to west to east, and rotate to the northwest to southeast orientation further north in the study area.

This study found that these deeper underlying structures may correlate to fracturing in the overlying Wasatch Formation. However, shallower Wasatch fractures may result from tension fracturing due to erosion and unloading of the basin. The fractures likely create higher permeability zones that enhance the movement of shallow groundwater to water wells Deeper fracture systems may also allow deeper formation water from the Wasatch and/or Mesaverde intervals to move upward and mix with shallower groundwater. The cementing problems encountered at the Schwartz 2-15B gas well are evidence that the presence of fractured intervals in this area may also affect cement integrity in gas well completions.

Hydrogeology

URS extracted the water well driller logs from the receipts database. The water well driller logs contained basic well drilling information covering a span of almost 45 years of well installations within the study area. Logs for 451 permitted wells were identified and reviewed. The number of wells completed for specific time periods is listed below. The total number of well completions has increased each decade, likely reflecting population increases in the area over the respective time periods.

- 1963-1970: 18 wells
- 1970-1980: 47 wells
- 1980-1990: 122 wells

- 1990-2000: 161 wells
- 2000-2005 (through April): 90 wells

The water well driller logs were reviewed for completeness and the relative quality log of the geologic log descriptions was entered into a specific data field. There were 311 geologic logs noted as Poor, 109 logs interpreted as Good, and only 17 Excellent geologic logs. The electronic well permit records were linked electronically in the Access database, allowing more rapid access to the paper copies. Significant data gaps were noted in the provided well information, primarily as omitted information, incomplete data or incorrect data due to data entry error.

Lithologic information for 430 permitted wells was available. Unfortunately, the geologic material for a large number of wells (190) were only noted as “Wasatch Formation”. Some of the most useful information was the “first observed water” notations and the water well test data completed when the pump was installed. The first observed water, or notations of where water was observed while drilling are the best indication of where the water is located in the subsurface. The static water level noted at the beginning of the water well test was utilized to construct a potentiometric surface map of the Wasatch Formation for this report. The production flow rate and final pumping level were used to calculate specific capacity at each well. Sustainable pumping rates for many of the Wasatch water wells are relatively low. This suggests that sufficient well yield is likely an issue of concern for many residents within the study area

The alluvial water wells are shallower than the bedrock wells, with a mean depth of 60 feet bgs, and screen lengths are correspondingly shorter. There is less variation in the total depth of alluvial water wells than for bedrock wells. Several wells are screened across alluvium and the underlying Wasatch bedrock. Based on the higher permeability of the alluvial sediments, most of the water produced from these wells is believed to come from the alluvial aquifer.

The recharge to alluvial groundwater is mainly from local and sub-regional rain or snow precipitation events and associated runoff. Irrigation return flow may also provide recharge to the shallow aquifer. The alluvial aquifer in the Colorado River alluvium is also recharged directly from bank recharges from elevated Colorado River surface water levels during flood or high water events. Other surface water bodies located within river valleys, including springs and ponds, may also recharge alluvial aquifers.

As compared to bedrock well completions, the alluvial aquifer wells have higher median specific capacities (2.2 gpm/ft versus 0.009 gpm/ft for bedrock wells) and higher median pumping rates (19.5 gpm versus 9.5 gpm for bedrock wells). This is not surprising since the alluvial aquifer generally consists of coarser, unconsolidated sediments that should result in higher values of hydraulic conductivity compared to the finer-grained and cemented materials comprising the bedrock aquifers. The majority of groundwater flow within the bedrock aquifer (Wasatch Formation) is likely due to fracture flow, and would be greater in areas that have a greater density of fractures.

Gas Well Activities

Sources of gas well data used in this study consist of the electronic database maintained by the COGCC, an on line database of scanned paper documents and interactive GIS mapping system maintained by the COGCC, and Petra software files provided by EnCana and BBC. The COGCC database is quite large. Due to the amount of paperwork required to permit, drill, complete, and produce hydrocarbons for each gas well, the large volume of data collected for each gas well, the different reporting requirements that evolved over decades, changes in well status, and staff availability at the COGCC, there are gaps (blank fields) in the data records in each of the COGCC databases. The gaps are difficult to fill efficiently from the on line database, given the large number of wells drilled in the area and the amount of available data.

URS reviewed the available data and focused on drilling and well completion information that could have the potential to allow upward migration of natural gas and fluids that could impact surface and groundwater resources. This included the depth of surface casing relative to the bottom depth of freshwater resources (the deepest water wells are 600 ft bgs in the study area), integrity of the production casing cement job (reflected in bradenhead pressure data), the depth to the top of gas, locations of plugged and abandoned wells, the age of abandoned and existing wells, locations of wells that experienced significant drilling and/or completion problems, and the relative density of subsurface fractures interpreted beneath various areas of the site.

Oil and gas exploration in the area dates back to 1959 with the drilling of the Starbuck #1 in the southeast corner of the study area and the Shaeffer well on Hunter Mesa. Only 23 gas wells were drilled prior to 1994, and 8 of these are still listed as producing. The oldest producing well is listed as completed in 1982. The gas wells produce natural gas, condensate, and water from sandstones of the Cretaceous Age Mesaverde Group, primarily the Williams Fork Formation fluvial sandstone units, as well as the underlying Corcoran, Cozette, and Rollins sandstones and Cameo coal. The reservoirs are tight gas sands, and the permeability of the reservoir must be increased to produce economic quantities of hydrocarbons. Production zones are hydraulically stimulated (“fraced”) using fluids (mostly fresh water with between 1 to 3 percent potassium chloride (KCL) added) and containing silica sand as a proppent and injected under high hydraulic pressure. Sand is mixed with the frac fluid and is forced into the fractures created. The sand “props” open the fractures when the pressure is released, and provides a pathway back to the wellbore to collect the gas. Mamm Creek Field has been developed on a roughly 20-acre downhole spacing with consolidation of wellheads and production equipment on multiwell pads minimizing surface development.

Approximately 978 wells have been drilled and completed and produce gas as of 2005. Between 1999 and 2005, 880 wells have been drilled and completed. The pace of new well completions has increased markedly during this period; however, due to the drilling moratorium around the West Divide Creek seep area, the pace may have decreased slightly during 2005. Thirty-six operators are listed as having drilled the 978 wells. However, many of the gas wells and associated appurtenances have changed ownership over the history of the field. EnCana is responsible for about 777 wells in the study area., and obtained wells previously owned by Ballard Petroleum and Alberta Energy Company (AEC).

Total depth of gas wells ranges from approximately 2,000 to 18,422 feet below ground surface (ft bgs). Average total depths of completed wells are between about 6,000 to 8,000 ft bgs. The top of gas in the Mesaverde group ranges from about 3,000 to 7,500 ft bgs across the study area. The depth to the top of gas is shallowest in the southeast corner of the study area, up on the Divide Creek anticline, and increases to the north and west, toward the central portion of the Piceance Basin.

Surface casing is set at each well prior to well drilling as part of the casing program, approved by the COGCC petroleum engineer, prior to issue of the Application for Permit to Drill (APD).

Surface casings are designed and set to a depth sufficient to protect all fresh subsurface water zones and to ensure against blowouts or uncontrolled well flows during drilling and is cemented from the total depth to the ground surface. In Mamm Creek Field, surface casing depths commonly exceed the maximum depth of usable subsurface waters with casing depth designed to maintain subsurface pressure control during well drilling and to provide borehole integrity in the upper portion of directionally drilled wells. Surface casing is required to be set at least 50 feet below the deepest water well within 1 mile of the new gas well. Because of well control issues, surface casing is required to be set to at least 10 percent of the total well depth, which typically exceeds the length needed to protect the fresh water aquifer. Surface casing depths range from 223 to 5,200 ft bgs. The majority of setting depths are between 700 and 1,200 ft bgs. The deepest water wells in the study area are 600 ft bgs. There are approximately 97 gas wells in the study area with surface casing shorter than 600 feet. Eleven gas wells within the study area have surface casing set from 223 to 400 feet bgs.

In July 2004, COGCC began requiring bradenhead monitoring of all oil and gas wells in the Mamm Creek field area. If a gas well has bradenhead pressures exceeding 150 psi, then the operator is required to notify the COGCC. From data provided to URS by COGCC, there were 148 gas wells with bradenhead pressures exceeding 150 psi at some point during 2004 and 2005. COGCC evaluates the pressure gradient at the surface casing shoe to determine if the rock fracture gradient is exceeded. The rock fracture gradient may have been exceeded at 3 of these wells, and the hydrostatic gradient was exceeded in an additional 12 wells. Most of the wells with elevated bradenhead pressures are located on the north-northwest flank of the Divide Creek anticline and within the Hunter Mesa area. It is speculated that there may be a correlation between elevated bradenhead pressures and the presence of linear features indicating the presence of underlying geologic structures, i.e. fractures. This potential relationship could be due to difficulties obtaining a cement bond with the production casing and borehole wall in fractured depth intervals.

Additionally, bradenhead pressures ranging from 100 to 400 psi were measured in 20 wells with surface casing set at depths of 600 ft or less.

Most wells drilled in the Mamm Creek Field require a reserve pit (also know as a drilling or mud pit) used to contain the drilling mud (mostly water with bentonite clay “mud”) used to maintain safe borehole pressures, minimize formation damage during drilling, provide cooling for the drill bit, and help circulate drill cuttings to the surface. These pits are not separately permitted by the COGCC and are part of the APD. At the end of well drilling and completion, reserve pits are dewatered and the remaining pit solids (mostly rock cuttings) buried. Reserve pits may be unlined or lined (usually poly liner) depending on depth to shallow ground water (required by COGCC rule) or by operator preference. The majority of reserve pits in Mamm Creek Field have been lined. In some cases, operators have also used the reserve pit as “completion” or “flow-back” pits used to flow-back fluids and gas from frac operations. Open pit flow-backs are usually done under a flare, where gas in the flow-back is burned. Residual petroleum hydrocarbons (condensate) that are sometimes intermittently produced during flow-back are also burned during flaring.

Since 2002, most Mamm Creek Field operators have used a multi-phase separator during frac flow-back where gas and occasional condensate have been separated from the flow-back fluids and the gas collected into sales lines and condensate into tanks. These flare-less completions are called green completions.

Oil & Gas operators can permit produced water pits for disposal (through primarily evaporation) of produced water from a well. This type of produced water disposal is not common in Mamm Creek Field, however; approximately 40 production pits were permitted with the COGCC by Mesa Hydrocarbons primarily in the lower portion of the Mamm Creek drainage. EnCana later purchased these wells and conducted closure of these pits with appropriate soils remediation where necessary.

There are documents on file with the COGCC that document the release of condensate and water at the ground surface from old plugged and abandoned wells within the study area. Older gas wells may not have been originally plugged and abandoned to the same standards as are currently required. Cement plugs and steel casing may also fail over a period of decades. URS is unaware of any routine monitoring program requirements for plugged and abandoned wells. There are currently 29 abandoned (temporarily abandoned, dry and abandoned, and plugged and abandoned), and 33 shut-in wells within the study area. Shut-in gas wells are considered active wells by COGCC, and require routine mechanical integrity tests (MITs). Bonding is required for some shut-in gas wells that remain inactive for extended periods.

Gas wells that experienced significant drilling and/or completion problems could potentially result in releases of hydrocarbon to the near surface environment. COGCC rules require that drilling and completion problems are reviewed by COGCC engineers, and approval must be obtained by operators prior to conducting remediation of well bore problems. It is time-consuming to identify individual wells in the database that have required remediation, and this was outside of the scope of this study.

URS evaluated the number of days to complete a well as a potential indicator of gas wells that may have had drilling or completion problems. However, since most gas wells in the study area are completed on multiple-well well pads, completion activities may not begin on the first well drilled on a pad until the other wells have been drilled and perhaps completed. The majority of wells are completed within 50 to 150 days. There are approximately 47 gas wells that are listed as requiring more than 200 days to complete, and 7 wells requiring more than 300 days to complete.

The original statement of work for this project requested information regarding the volume, handling and disposal of produced water. The flowrate of produced water during the initial completion test is recorded for most gas wells in the COGCC database. It is unknown how the initial production rates compare to production rates over time for the individual wells. This includes data for both typical gas wells and approximately 30 coalbed methane (CBM) gas wells. CBM wells generally have significantly higher water production rates, especially the initial flowrates, because the coalbed(s) need to be dewatered to produce the natural gas. CBM wells are located in the southeast and east-central region of the study area. Production rates from the initial test data range from <1 to 1,677 barrels of water per day. The average water production rate is 152 barrels per day (6300 gal per day or about 4 gpm). The combined production rate from all 790 wells listed in the database is 120,243 BBL/day, or 5,050,198 gal/day, or 3,507 gpm. Although cumulative production data is maintained on the COGCC on-line database, the information can only be accessed for one gas well at a time.

URS requested cumulative water production data from EnCana for wells within the study area. The data show that produced water rates relative to gas production rates are highest in the southeast portion of the study area, near the Divide Creek anticline, and decrease to the north and northwest. The highest water production rates occur in the area where many of the CBM wells are located. The total recorded volumes of gas, condensate, and water are 308,398,672 MCF, 2,003,487 BBL (84,146,445 gal), and 10,088,296 BBL (423,708,442 gal), respectively.

Produced water, and condensate, is stored within ASTs located on each well pad. Condensate is sold as crude oil, and recovered periodically from the AST. The produced water is periodically removed from the tanks and transported by truck to an evaporation pond located in the study area for evaporation (disposal) or treatment and beneficial reuse where applicable and allowed by COGCC rules.

A new water treatment facility has been constructed on Hunter Mesa The Hunter Mesa Centralized E&P Waste Management Facility was permitted by the COGCC in December 2003 and provides water disposal (evaporation) in addition to beneficial reuse of produced water. The facility also is conducting a water treatment pilot test where CBM water from the Divide Creek CBM test is treated to provide low total dissolved solids water for make-up drilling and completion fluids. Waste streams from this process are disposed via two injection wells adjacent to the facility. Both wells are completed for injection into the Corcoran sandstone located below the Williams Fork sandstones. Water is also handled at the former Snyder (now EnCana) operated Centralized E&P Waste Management Facility located off Dry Creek Road and at the Fox Lake Centralized E&P Waste Management Facility on Grass Mesa.

URS has evaluated a portion of the existing data related to gas well drilling, completion, and production activities within the study area. Results of this evaluation can be used as leads to focus on specific wells that may require additional data evaluation in the COGCC on line database or potentially field reconnaissance and investigation.

Water Quality

Water quality data was integrated with lithologic (e.g., alluvial or Wasatch Formation aquifer), well depth, and specific capacity data for the water well completions, To integrate the data, URS attempted to index the water quality locations, which have GPS survey coordinates, to locations of SEO permitted water wells, that use quarter-quarter section or distance from the nearest section lines for locations. Only about two-thirds of the locations could be reliably correlated.

For major ion chemistry, the existing data were checked by calculating the charge balance for cations and anions. A total of 220 groundwater sample and 61 surface water sample locations were selected for evaluation based on a calculated maximum charge balance error of plus or minus 10 percent. Most sample locations have been sampled only a few times; and evaluation of temporal concentration trends was not performed for this study.

URS evaluated the major ion data to determine water types (e.g., Na-Cl type), and constructed Piper plots, Schoeller plots, and Stiff plots. Principal component analysis (PCA) was performed on the major ion datasets as one method to evaluate the variance in water types. Cluster analysis was also performed on these data sets as another method to divide the data into distinct water types.

Of the 220 groundwater sample locations considered suitable for major ion evaluation, 195 wells are domestic wells, 21 are monitoring wells located at the West Divide Creek seep area, and 4 are irrigation wells. The inferred geology for the water well completions consists of 67 locations in the Atwell Gulch member, 62 locations in the Shire member, 72 locations in the Molina-like sandstone unit, and 19 alluvial aquifer locations. There are very few water wells located on Hunter Mesa and within the southwest quadrant of the study area due to sparse residential settlement.

Sodium is the dominant cation and bicarbonate is the dominant anion at more than 60 percent of the locations. The most frequent water types are Na-HCO_3 (49 locations), followed by Na-SO_4 (22), Na-SO_4-HCO_3 (16), Na-Cl (15), with various Ca and/or Mg-HCO_3 waters accounting for 41 more locations. Groundwater with higher TDS values (>1,500 mg/L) is generally of the Na-Cl or metal sulfate type (i.e., Na-SO_4). Metal bicarbonate (i.e., Na-HCO_3) water types comprise samples with lower TDS concentrations (<1,000 mg/L). Principal component and cluster analysis of major ion data offered little in explaining which ions were most influential for explaining water type variances.

The sodium-sulfate water type occurs primarily in the Dry Hollow Gulch area, where Dry Hollow Road enters the narrow portion of the stream valley (Sec 3 T7S92W and Sec 33 and 34 of T6S 92W), and Na-Cl water types are also found in this area, specifically at well locations just downstream from the start of the narrow valley. It is speculated that the high-TDS Na-Cl type waters may be derived from deeper groundwater of higher salinity, perhaps diluted by mixing with shallower groundwater. The deep groundwater may migrate toward the surface within fracture zones that may be related to structures like the Divide Creek anticline.

The origin of the Na-SO_4 water type in the Dry Hollow area is unknown. Sulfate concentrations in produced water samples from gas wells within the study area are typically non-detect. However, some groundwater researchers have documented the presence of sulfate as the dominant anion in groundwater from the “intermediate zone”. The intermediate zone is broadly defined as below the upper zone (where bicarbonate is the dominant anion) and above the deep zone (where chloride is the dominant anion).

Sulfate is not typically associated with deeper groundwater where natural gas or other hydrocarbons are documented to be present. The hydrocarbons serve as energy sources to bacteria, which consume oxygen and other electron receptors and drive the water chemistry to reducing conditions. Under reducing conditions, sulfate-reducing bacteria consume sulfate present in the groundwater to oxidize carbon sources, thereby decreasing sulfate concentrations.

The water types in the Dry Hollow area may result from mixing of shallow, intermediate, and deeper water sources. The upper Molina-like sandstone unit is thick and relatively massive in this area of Dry Hollow Gulch, and there are a number of linear structures mapped in this location. Water well yields (as reflected by specific capacity calculations) are high in this area, which is interpreted to reflect the presence of a fracture zone that enhances the permeability of the Wasatch Formation bedrock.

It is speculated that most shallow groundwater in the study area starts out as metal bicarbonate waters (Ca-HCO_3 or Mg-HCO_3 water), which evolve and pick up sodium ions through ion exchange processes. As the sodium increases, the residence time of the water is increasing, and the TDS also increases. An alternate theory is that the bedrock contains sufficient sodium in a mineral form to provide sodium to groundwater. Some of the Ca, Mg, and bicarbonate may also be lost as the water “ages” through precipitation of Mg-bearing calcite.

Fluoride concentrations in groundwater are highest (approximately 10 mg/L) in the area around the nose of the Divide Creek anticline (Sec 34 T6S 92W), and may indicate the presence of water from deeper within the Wasatch Formation or a deeper formation. The EPA drinking water maximum contaminant level (MCL) for fluoride is 4 mg/L.

Selenium concentrations also exceeded groundwater standards in several domestic water wells. The MCL is 0.05 mg/L, and groundwater concentrations ranged as high as 1 mg/L.

Benzene and other hydrocarbon constituents were detected in a number of monitoring wells as part of the monitoring network for the shallow groundwater remediation at the West Divide Creek seep area. Benzene was not detected in domestic water wells in the study area.

Concentrations of dissolved methane were detected at many domestic water well sample locations. Concentrations ranged from non-detect up to 37 mg/L. Although the presence of methane in groundwater could be interpreted as indicating a release of natural gas from drilling operations, analysis of isotopic species and gas composition have shown that biogenic methane is present in many wells in the area. Methane can form from biologic processes which include fermentation or oxidation of carbon dioxide. The biogenic methane can even be formed within a water well. Based on stable isotope ratios, many of the domestic wells with methane where additional analyses have been completed show that they contain biogenic methane. However, three domestic wells have ratios which plot in an area located between biogenic and thermogenic methane. These three wells have methane of uncertain origin, which may be gas from multiple sources. Where stable isotope data is available for monitoring wells located in the West Divide Creek seep area, analysis suggests the methane is of thermogenic origin. There are approximately 29 water wells where methane was detected above 1 mg/L, which have not been evaluated for isotopic constituents delta carbon (C) of methane and delta deuterium (D) of water, or the presence of other gases (i.e. ethane, propane, iso-butane, iso-pentane, and hexane).

Groundwater samples exceeded the Colorado basic groundwater standards and domestic water supply standards for a number of constituents. Ten to 15 percent of the samples from domestic wells exceeded the standard for chloride, fluoride, nitrate, and selenium. The standard for iron and manganese was exceeded by about 25 percent of the domestic well samples. For irrigation wells, the agricultural standard was exceeded for roughly 20 percent of the samples for chloride, fluoride, and iron, and almost 50 percent of the samples exceeded the selenium and sulfate standards. Sixty-six percent of the irrigation wells samples exceeded the nitrate groundwater standard.

The most frequent water types in Shire rocks are: Na-HCO_3 (9 sampling locations), Ca-Mg-HCO_3 (8), Mg-HCO_3 (8), Mg-Ca-HCO_3 (7), and Mg-Na-HCO_3 (5). Wells located on Grass Mesa are all completed in the Shire member of the Wasatch Formation and generally had the lowest TDS concentration values and are rich in bicarbonate. The low-TDS concentration suggests that the Grass Mesa groundwater originated from local infiltration of rainwater and snow-melt. By contrast, high-TDS Na-Cl water-types were observed in several wells located both east and west of Grass Mesa, but not on the mesa. These locations are located along a linear aeromagnetic anomaly, and may reflect upward movement of deeper formation waters. The high-TDS water probably has a deeper source because TDS, sodium, and chloride concentrations often increase with the age or residence time of the groundwater. Major ion analysis of several samples obtained from producing gas wells show a Na-Cl water type with high TDS concentrations.

The most frequent water types in the Molina-like sandstone unit are: Na-SO_4 (19 locations), Na-HCO_3 (9), Na-Cl (8), Na-HCO_3 (6), Mg-Na-HCO_3 (3), and Mg-HCO_3 (3). Mixtures of different water-types were found at 23 additional Molina-like sandstone unit locations.

Na-Cl water-types are more common in the lower portion of the Molina-like sandstone unit (west and north edge of the outcrop area). The source of the Na-Cl is unknown, but likely represents deeper formation water or a mixture of shallow water and deeper formation water. Wells completed in the upper portion of the Molina-like sandstone unit display fewer Na-Cl water types.

Na-SO_4 waters are common in both the upper and lower portions of the Molina-like sandstone unit in the area of Dry Hollow Gulch where the valley narrows in Section 3 T7S R92W. The origin of the sulfate is unknown but may be derived from the oxidation of bedrock containing more pyrite (FeS_2).

The most frequent water types in Atwell Gulch rocks are: Na-HCO_3 (28 locations), Na-SO_4-HCO_3 (6), Ca-Mg-HCO_3 (5), and Ca-HCO_3 (5). Mixtures of other water-types were found at 23 other Atwell locations. Na-Cl waters are uncommon but occur as relatively high-TDS waters in the southeast portion of the study area.

Alluvial aquifer water samples were all located in the West Divide Creek seep area. The water types are Ca-HCO_3 and/or Na-HCO_3 water-types, including: Ca-HCO_3 (7 locations), Na-Ca-HCO_3 (4), Ca-Na-HCO_3 (4), Na-HCO_3 (3), and Ca-Na-Mg-HCO_3 (1). Na-Cl water-types were not detected in the sampled alluvial groundwater.

Major ion chemistry was evaluated from 61 surface water samples that had a charge balance within plus or minus 10 percent. Out of the 61 sampling sites, 22 are associated with alluvium, 18 are overlying the Shire member of the Wasatch Formation, 9 overlie the Molina-like sandstone unit, and 12 are overlying the Atwell Gulch member. Spring waters represent 33 of the 61 sites, stream waters were sampled at 18 sites, and 10 locations represent pond waters.

Bicarbonate-type waters are the most common surface water-types. Water-types with the highest frequency are: Mg-HCO_3 (11 occurrences), Na-HCO_3 (9), Ca-Na-HCO_3 (7), Ca-Mg-HCO_3 (7), and Ca-HCO_3 (7).

The highest frequency water-type in pond waters is Ca-Mg-HCO_3, followed by Mg-Na-HCO_3, and Mg-HCO_3. Water-types with the greatest frequency in springs are: Mg-HCO_3 (9 stations), Ca-HCO_3 (5), and Ca-Mg-HCO_3 (4). Stream waters in the study area are often Na-HCO_3 type waters (5 occurrences), or Ca-Na-HCO_3 (5), or Na-Ca-HCO_3 (3).

The water-types with the highest-TDS are predominantly Na-SO4 or Na-Cl waters, similar to what was seen in groundwater. The low-TDS (<900 mg/L) waters are of a metal bicarbonate type, again similar to groundwater. Most of the low-TDS waters are Ca or Mg bicarbonates.

The TDS of the surface waters has a lower range (up to 3000 mg/L) than groundwater (up to 6000 mg/L). The highest-TDS water-type is a Na-SO_4 water located west of Dry Hollow Creek. One Na-Cl rich water-type is observed in the extreme southeast corner of the study area, and a Na-Cl groundwater was also described in Atwell Gulch rocks near this area. A pond water sample from Grass Mesa is a Mg-Na-HCO_3 type water and displays a higher TDS (probably from evaporation), and a different chemistry than the Shire groundwater samples evaluated in this area.

The highest fluoride concentration is 8 mg/L in spring water in the southeast corner of the study area. This is the only surface water sample that exceeded the 4 mg/L MCL for fluoride. Fluoride concentrations in groundwater were also elevated in this area.

Nitrate concentrations from samples obtained at a spring located on the east edge of the study area have varied widely from nondetect (<1.3 mg/L) up to 70.8 mg/L, during the period January 2003 to July 2005. An agricultural source of nitrate is suspected, such as a nearby fertilizer application. The next highest nitrate concentration is only 11.3 mg/L at another spring located southeast of Grass Mesa in Section 10 T7S 93W. The drinking water MCL for nitrate is 10 mg/L.

Methane was not detected in most of the water samples that have been collected in the western portion of the study area (Grass and Hunter Mesa). When methane was detected, it was at very low concentrations. The origin of the methane at these low concentrations was not determined because analysis of stable isotopes of methane when it occurs at such low concentration has not been required or recommended by the COGCC, and until recently could not be reliably done. There are very few water wells located on Hunter Mesa, and a great number of gas wells. Groundwater quality for a large portion of this area is essentially unknown.

Methane has been detected at elevated concentrations in a number of water well locations in the eastern portion of the study area. Based on work performed by COGCC, in the vicinity of the West Divide Creek gas seep and the G33 pad area groundwater and surface water have been impacted by thermogenic methane related to gas development activities.

In the southeast portion of the study area, extensive water sampling has detected some of the highest concentrations of methane. There has been relatively little drilling in the vicinity of the Divide Creek area. However, some older gas wells are present within this area. It is likely that releases from inadequately plugged and abandoned wells, and wells where significant completion problems were encountered, are a source of methane to groundwater in this area. The PhilPott JO #1 well located in the NWNW Section 36, T7S, R92W was drilled to a total depth of 5,425 feet and then plugged and abandoned in 1966. The plugging record indicted that the annulus was still under pressure during plugging. Almost 30 years later the landowner discovered that the well was leaking oil and water to the surface. In 1994 the well was plugged by the COGCC. It seems that after almost 30 years of leaking, a large quantity of gas and oil could have been released to the aquifer and that even after the plugging in 1994, lingering impacts to groundwater and surface water may exist in this area.

During the pre-bid meeting for the proposal, it was mentioned that groundwater quality in the area was relatively poor, and that some residents may blame the oil companies for the poor quality, but that water quality may be more directly related to geologic conditions in the Wasatch Formation. Specifically, it was mentioned that the lack of lateral continuity of sandstone units, and the predominance of mudstone lithologies in the Wasatch Formation could be causing the observed variations in water quality between domestic water wells. The results of this study suggest that lithology alone does not determine water quality. The most desirable water quality (low TDS, and no exceedances of MCL levels) appears to be in areas where water is located at shallower depths and/or near sources of recharge. Concentrations of calcium, magnesium, and bicarbonate in area water wells generally decrease with depth. Conversely, an increase in concentration with well depth is observed for sodium, sulfate, and chloride. TDS concentrations also show an overall increase with depth of the water well.

1.1 SCOPE AND OBJECTIVES

The scope of this project was defined in the Memorandum of Understanding signed in March 2005 by the Colorado Oil and Gas Conservation Commission (COGCC), the Board of County Commissioners of Garfield County, EnCana Oil & Gas (USA) Inc. (EnCana), Western Colorado Congress, and Grand Valley Citizens' Alliance (related to Order No. 1V-276). The scope was further developed in the original request for proposal. The site location is an area in Garfield County located south of the towns of Rifle and Silt, Colorado. Since about 1999, this area has experienced a surge of drilling activity for natural gas in and around the Mamm Creek field.

As stated in the scope of work, "The primary objective of this study is a comprehensive investigation of the groundwater and surface water resources of an area within Garfield County and an analysis of their vulnerability to impact from natural gas exploration and other human activities."

The eight tasks included in the scope of work are:

1. Describe the regional hydrogeology of the Wasatch Formation including the distribution of potable water resources and determine the geologic framework (lithology, facies, and stratigraphy) using geophysical logs from oil and gas wells, water well drillers logs, and outcrop studies.
2. Describe the geologic and structural controls of the surface water and alluvial groundwater and evaluating recharge/discharge relationship between surface water and the adjacent groundwater resources.
3. Describe the hydrochemistry of the groundwater in the Wasatch Formation, surface water, and the adjacent alluvial groundwater.
4. Describe the regional geologic setting including identifying and mapping faults, fractures, and lineaments using geologic maps and satellite/aerial photos and other published data.
5. Compile data from oil and gas wells.
6. Analyze, interpret, and synthesize data, including data from oil and gas wells, to determine whether there are yet unidentified areas where groundwater or surface water have been impacted or have a higher potential to be impacted by oil and gas exploration, development, and production. Areas where naturally occurring accumulations of gas in the Wasatch Formation or Quaternary alluvium have the potential to be encountered by water well drilling and development will be identified and mapped. The distribution of other anthropogenic (nitrate/nitrite) or naturally occurring (selenium or fluoride) contaminants of concern will also be identified and mapped.
7. Recommend a plan for Phase II.
8. Conduct public outreach

To allow compilation and evaluation of existing data for the 110 square mile area, existing data for the focused studies regarding the occurrence of thermogenic methane in the Amos/Walker and Dietrich water wells and the West Divide Creek Seep area was not reviewed or included in this report.

1.2 STUDY AREA LOCATION AND DESCRIPTION

The study area is located in northwest Colorado in southern Garfield County, near I-70 between Glenwood Springs and Grand Junction, and lies south of the cities of Rifle and Silt (Figure 1-1). The study area is defined as the area south of the Colorado River in four townships: townships 6 and 7 south (6S, 7S) and ranges 92 and 93 west (92W, 93W). The study area includes portions of 127 sections, and measures approximately 110 square miles in size. Within the study area, the ground surface ranges from an elevation of 9,400 feet above mean sea level (ft MSL) in the southwest corner above West Mamm Creek (on the northeast flank of Battlement Mesa), to a low of 5,280 ft MSL along the Colorado River in the northwest corner near the town of Rifle.

The study area includes (listed from west to east) the eastern portion of Taughenbaugh Mesa, and all of Flatiron Mesa, Grass Mesa and Hunter Mesa. Battlement Mesa and Grand Mesa, both located outside the study area to the southwest, are the highest terrain in the area. Annual precipitation ranges from a low of 12 inches at low elevations (along the Colorado River valley) to almost 30 inches per year in the higher elevations (flanks of Battlement Mesa).

The stream drainages and gulches in the study area include, from west to east, Beaver Creek (very small portion), Helmer Gulch, Ramsey Gulch, Dry Creek, West Mamm Creek, Gant Gulch, Middle Mamm Creek, East Mamm Creek, Mamm Creek, Dry Hollow Creek, Alkali Creek, West Divide Creek, East Divide Creek, and Divide Creek. There are several irrigation ditches in the study area, primarily in the eastern half and along the Colorado River valley. These ditches include the Porter Ditch, Highline Ditch, West Divide Creek Ditch, and Multa Trina Ditch, and the Mineota Ditch in the eastern area, and Rising Sun Ditch, and Last Chance Ditch along the south side of the Colorado River valley.

1.3 REPORT ORGANIZATION

Although the original RFP for the Phase I study was arranged into eight tasks, this report is divided into major sections by discipline, i.e., geology, hydrogeology, petroleum hydrocarbon production, and water quality. Each report section begins with a discussion of the existing available data and where it was obtained and how it was utilized. Within each major section, a regional discussion of the discipline (e.g., geology) is followed by more detailed discussions for different portions of the study area, as appropriate based upon the distribution and quality of existing data.

This section of the report describes the geology of the study area as it pertains to surface water and groundwater resources. It includes descriptions of the stratigraphy and regional trends in the Wasatch Formation, and regional geologic structural features that could serve as migration conduits for deeper groundwater and natural gas to reach the ground surface. Therefore, the surficial geology discussion pertains predominately to the shallow water-bearing intervals in the Wasatch Formation and alluvium adjacent to the major stream drainages. Geologic maps of the area breakout a number of different surficial deposits associated with relatively recent-aged alluvial, colluvial, and eolian deposits. These units are not typically water-bearing in this area and are not discussed in detail in this report.

During the pre-bid meeting for the proposal, it was mentioned that groundwater quality in the area was relatively poor, and that some residents may blame the oil companies for the poor quality, but that water quality may be more directly related to geologic conditions in the Wasatch Formation. Specifically, it was mentioned that the lack of lateral continuity of sandstone units, and the predominance of mudstone lithologies in the Wasatch could be causing the observed variations in water quality between domestic water wells. One of the geologic tasks specified in the RFP was to "determine the geologic framework (lithology, facies, and stratigraphy) using geophysical logs from oil and gas wells, water well drillers logs, and outcrop studies."

2.1 GEOLOGIC DATA SOURCES AND DATA COMPILATION

Existing information regarding the geology of the study area is available in the scientific literature, and in the water well drillers logs and gas well electric logs. Literature references are cited in the report text and can be found in Section 8. Recent geologic maps are also available and cover portions of the study area. These maps include the Rifle, Silt, and North Mamm Creek quadrangles (Shroba and Scott 1997, Shroba and Scott 2001, and Donnell1989) and the Hunter Mesa quadrangle (Madole 1999).

One of the few project tasks involving the collection of new data for the site was the Wasatch outcrop study. This task was performed to better evaluate the lateral continuity of individual sandstone units comprising the Wasatch Formation in the study area. URS geologists measured five outcrop sections located around the study area.

URS also obtained Petra database files containing gas well borehole logs from both Bill Barrett Corporation and EnCana Corporation. This information was used to produce cross-sections and isopach maps for the study area. Some of the individual logs were also evaluated to the extent possible within the scope and timing of the project.

URS was also able to examine rock core of the Wasatch collected by EnCana from their Moore 33-10A well. A CD-ROM with photos of the core was given to URS at the job kickoff meeting in early July 2005, and the core was made available to URS at a local core warehouse.

2.2 REGIONAL GEOLOGY

The study area is located within the southeast portion of the Piceance Basin, or the Piceance Creek Basin as termed in earlier literature. The Piceance Basin is a large sedimentary basin and structural depression formed during the Laramide Orogeny, which occurred between the Late Cretaceous and Eocene time periods, approximately 70 to 40 million years ago (Johnson and Flores 2003). The thickness of sedimentary rocks in the basin reaches 28,000 feet, with rocks ranging in age from Cambrian to Eocene (490 to 33 million years ago) (Johnson and Rice 1990). The southern portion of the basin is bounded by uplifts, including the Douglas Creek Arch to the west, Uncompahgre Uplift to the southwest, the Sawatch Uplift to the southeast, and the White River Uplift to the northwest. The Grand Hogback monocline is located immediately northeast of the study area, near the structural axis of the basin, which trends northwest-southeast in this area (Tremain and Tyler 1996). The surface expression of the basin margins is expressed by outcrop of rocks of the Mesaverde Formation (Figure 2-1).

There are several northwest-trending anticlines in the southern portion of the basin, and one of these, the Divide Creek anticline, is located immediately southeast of the study area. The plunging nose of this anticline extends northwest and into the study area. The presence of regional structural features associated with the Divide Creek anticline are potentially important with respect to water well yields and water quality.

This report focuses on bedrock units of the Mesaverde and Wasatch Formations. Gas wells drilled in the study area typically have total depths between 6,000 to 10,000 feet below ground surface, and rarely extend to depths below the Mesaverde. Figure 2-2 is a simplified stratigraphic column for rocks of interest beneath the study area. From oldest to youngest, the rock units of interest beneath the study area are the Mancos Shale of Upper Cretaceous age, the Iles Formation and the Williams Fork Formation (Mesaverde Group), the lower Tertiary Wasatch Formation, and the Green River Formation (Lorenz 1982, Hemborg 2000). Only the Wasatch and Green River Formations outcrop within the study area. The Williams Fork outcrops to the southeast, on the Divide Creek anticline. The Green River Formation is present only up on the north flank of Battlement Mesa, in the southwest corner of the study area. The Wasatch Formation is present at the ground surface beneath roughly 90 percent of the study area, and is discussed in more detail in the next section.

The Mancos Shale (Upper Cretaceous age) represents a time period when a marine sea environment occupied a broad portion of the Rocky Mountains. The Iles Formation, deposited in marginal marine to lower coastal plain environments, intertongues with the upper Mancos Shale. The main sandstone reservoir intervals in the Iles Formation (bottom to top) are the Corcoran, Cozzette, and Rollins sandstone members.

Overlying the Iles Formation are Upper Cretaceous-aged rocks of the Williams Fork Formation of the Mesaverde Group. The Cameo-Fairfield coal zone is located in the lower portion of the Williams Fork, and is an important resource in the county. The coal is mined in other portions of the Piceance Basin, and is a coalbed methane play beneath the southeast portion of the study area. Sandstones of the Williams Fork were deposited in a fluvial environment and constitute the primary gas reservoir lithology in the Mamm Creek field. Non-marine Mesaverde Group reservoirs also produce the majority of the natural gas in the Rulison Field, located immediately west of the study area (Peterson 1984). A regional Paleocene-aged unconformity occurred following deposition of the Williams Fork, and is represented by the Ohio Creek Conglomerate in some areas of the southern basin. The Wasatch Formation, deposited in upper coastal plain, fluvial and alluvial environments, overlies the Williams Fork beneath the study area, and is discussed in more detail in the following section.

The Green River Formation conformably overlies the Wasatch Formation in the study area, and consists largely of fine-grained rocks resulting from lacustrine deposition in the former Lake Uinta. The Mahogany Bench member of the Green River Formation is the source of the oil shale in the Roan Cliffs area. The lake shifted from initial freshwater conditions and gradually became more saline as the Eocene progressed (Johnson 1985).

2.2.1 Wasatch Formation

Approximately 90 percent of the water wells within the study area are screened within consolidated mudstones and sandstones comprising the Tertiary-aged Wasatch Formation. The remaining 10 percent are completed within Quaternary-aged alluvial deposits in stream valleys. An understanding of the origin of the Wasatch Formation sediments and their burial history provides a useful framework to evaluate regional water quality and water chemistry data trends.

The Wasatch Formation (Wasatch) is widespread in the northern Rockies, and occurs in most of the Rocky Mountain states. This includes northwest New Mexico (San Juan Basin), Colorado (Piceance Basin), Utah (Uinta Basin), Wyoming (Washakie and Powder River Basins, Idaho-Wyoming Thrust Belt), Idaho (Idaho-Wyoming Thrust Belt), South Dakota (flanks of the Black Hills), and Montana (central and eastern portions) (Bernhardt et al. 1982).

In Colorado, Donnell (1969) defined three stratigraphic members of the Wasatch in the southern Piceance Basin based on outcrop near the town of Molina, Colorado, which is located approximately 20 miles southwest of the study area. Near Molina, the Wasatch Formation varies from approximately 1,800 to 3,500 feet thick and is divided, in ascending order, into the Atwell Gulch, Molina, and Shire members. These sedimentary rocks occur between the Ohio Creek Formation and the Green River Formation, and were assigned ages from late Paleocene to Eocene based on paleontological evidence (Donnell 1969).

The Mesaverde Group and much of the Wasatch are exposed in outcrop along the Grand Hogback at Rifle Gap State Park, located approximately 5 miles northeast of Rifle. The beds exposed in the Rifle Gap area are steeply dipping ranging from nearly vertical to slightly overturned. Dips decrease to the south toward the basin axis. Numerous petroleum geologists and engineers have studied the older Upper Cretaceous portion of the outcrop, as these units are reservoir rocks in nearby Piceance Basin gas fields. Donnell (1969) visited these outcrops and evaluated the Wasatch units, and this area was also mapped by the USGS (Shroba and Scott 1997 and 2001). Shroba and Scott defined a new member, the Doodlebug Gulch member, which caps the Wasatch in the northwest portion of the Rifle quadrangle (1997), and an informal unit, the Sandstone Unit of the Shire member in the Silt quadrangle (2001). Neither of these units was mapped within the study area.

As described by Donnell (1969), the Atwell Gulch member consists mostly of purple, lavender, red, and gray claystone with minor gray and brown lenticular sandstone units near the base. The Molina consists of “massive brown, gray, red or green persistent sandstone beds with minor claystone. “ The Shire member is dominated by red, purple, lavender, and gray mudstones with subordinate volumes of poorly bedded lenticular sandstones near the base. Resistant lenticular brown ledge-forming sandstone beds separated by red claystone also occur in the upper portion of the section near the contact with the overlying Green River Formation (Donnell 1969).

The members of the Wasatch were also described by Shroba and Scott (1997, 2001), from their mapping work on the Rifle and Silt quadrangles and are summarized below. Much of the exposures are located along the flanks of the Grand Hogback. The southern portions of these quadrangles extend into the northern portion of the study area.

Shire Member – Nonmarine, predominately multicolored fine-grained clastic intervals with less abundant intervals of minor coarse-grained clastic beds of fluvial sandstone. Mudstones are various shades of pale red, pale purple, reddish brown, yellow, and gray. Sandstones form less than 3 percent of the member, typically cross-bedded, with channels 1 to 10 feet deep and 30 to 80 feet wide, with coarse sand and lenses of pebble conglomerate at the base. In the Silt quadrangle, the Shire member is up to 3,900 feet thick. Shroba and Scott (2001) also named an informal sandstone unit that occurs on Davis Point, located about 1,000 feet above the base of the Shire. In the Rifle quadrangle, the Shire is about 5,000 feet thick, and is noted to pose a geologic hazard due to landslides on the steeper slopes of some mesas. They also named a new member, the Doodlebug Gulch member, which consists of about 14 thin sandstone units interbedded with mudstones, that caps the Shire northwest of the town of Rifle.

Molina Member – Nonmarine, predominately fine-grained, multi-colored mudstone units similar to the Shire member. Shroba and Scott (1997 and 201) state that, "the Molina member is distinguished from the Shire member by the presence of about 20 percent sandstone beds that are more resistant than those of the Shire because they are thicker and more strongly cemented by calcium carbonate." The sandstone is very pale orange, grayish orange, and yellowish gray, and commonly contains clay rip-up clasts 1 to 4 cm long. The thickness ranges from 300 to 1,200 feet in the two quadrangles.

Atwell Gulch Member – Nonmarine, and includes a volcaniclastic-rich upper part consisting of predominately multicolored fine-grained clastic intervals with thinner intervals of coarse-grained volcaniclastic beds of fluvial sandstone and conglomerate. The lower part is largely nonvolcanic and consists mostly of thick mudstone intervals with thinner fluvial sandstones and sparse conglomerates.

In the subsurface, petroleum industry geologists have termed a sandstone-dominated interval within the Wasatch located about 2,000 feet above the Fort Union Formation that produces natural gas in several Piceance Basin fields as the "Wasatch G" (Carlstrom 2003). This "concentration of fluvial sandstones" (Carlstrom 2003) may be the subsurface expression of the Molina member. The Wasatch G has produced substantial natural gas northwest of the study area in the Parachute and Piceance Creek fields, and lesser amounts in the Sulphur Creek and Trail Ridge fields (Carlstrom 2003). The Wasatch G is shown in the stratigraphic column in Figure 2-2. Although individual sandstone beds cannot be correlated laterally for any significant distance, the Wasatch G (sandstone) interval is laterally persistent beneath a large area of the southern Piceance Basin. However, the Wasatch G interval thins considerably in the subsurface beneath the study area (Plate 3 of Johnson and Flores 2003).

2.2.2 Regional Wasatch Correlations from Gas Well Logs

URS received digital log data in Petra format from both BBC and EnCana for many of the wells within the study area. These data were used to construct the three regional structural cross-sections and a Wasatch isopach map. The cross-section locations are shown in Figure 2-3, which also illustrates the interpreted distribution of the Wasatch members within the study area. The cross-sections and isopach map are shown in Figures 2-4, 2-5, 2-6, and 2-7. The cross-sections are hung based on ground surface or Kelly bushing elevations.

The stratigraphic correlations for the top of the Mesaverde Formation and top of gas shown in the cross-sections are based on the Petra formation tops file supplied with the Petra data, and reflects the combined efforts of BBC and EnCana geologists for several hundred gas wells in the area. URS did not verify the picks. The contact between the top of the Mesaverde Formation and the overlying Wasatch Formation is typically associated with a drop in resistivity (AT 90 log track). Log resistivity values near the top of the Mesaverde range from about 20 to 200 ohm meters (ohmms). In the overlying Wasatch, log resistivity values are generally less than 10 to less than 100 ohmms. The resulting log curves show a shift and reduction in the resistivity baseline in the Wasatch Formation as compared to the underlying Mesaverde.

As identified from the gamma ray curve, this log contact for the base of the Wasatch is often within an interval of interbedded sands and mudstones. This package is relatively sand-rich as compared to higher up in the Wasatch section and shows an overall fining-upwards trend from the Mesaverde into the lower Wasatch interval. The lower portion of the Wasatch generally has numerous thinner sand units in the basal 500 to 1,200 feet, and is overlain by a mudstone-dominated interval approximately 1,500 to 4,500 feet thick (e.g., EnCana Kell 35-4A).

As shown in the northwest to southeast cross-section A-A', Figure 2-4, the thickness of the Wasatch varies from approximately 1,200 feet in the southeast corner of the study area (Divide Creek Land and Cattle 23-8B) to 5,400 feet in the northwest corner (EnCana GMR 22-4A). The base of the Wasatch, corresponding to the top of the Mesaverde, dips northwest approximately 4.5 to 5 degrees (about 80 to 90 feet of drop per 1,000 feet of horizontal distance). The dip is subtler from east to west (Figure 2-5, Cross-section B-B'), with a dip angle of about 1.4 degrees (24 feet of drop per 1,000 feet of horizontal distance). Cross-section C-C' (Figure 2-6) is oriented roughly north-south along the east side of the study area, somewhat in line with the plunge of the Divide Creek anticline. The dip on top of the Mesaverde is approximately 6 degrees (100 feet of drop per 1,000 feet of horizontal distance).

The Wasatch G interval (Molina sandstone equivalent) may be difficult to identify on gas well borehole logs beneath the central and eastern portions of the study area because it is present at shallow depths in many areas and outcrops in the eastern portion of the area. Gas well borehole logs have not historically been obtained from open-hole logging tools in the upper portions of gas wells where the surface casing is located. However, the persistent sandstone units visible in outcrop on the east side of the study area, are not obvious in borehole logs from gas wells located on the west side of the study area. Based on the dip angle calculations for the Mesaverde top, the Molina sandstone exposed west of Divide Creek, would be at a depth of about 2,500 ft below ground surface (bgs) and an elevation of about 3,900 ft mean sea level (MSL) below the central portion of the Grass Mesa area (cross-section A-A', Figure 2-4). On cross-section C-C' (Figure 2-6), the Molina sandstone should be located at a depth of about 1,650 ft bgs or an elevation of about 4,000 ft MSL beneath the area north of Weible Peak and south of Silt in Section 15, T6S 92W.

Figure 2-7 is an isopach map constructed for the Wasatch interval from the Petra database file. Since the Wasatch is present at the ground surface in the study area, the thickness is largely a result of erosional processes occurring sometime after deposition. The Wasatch thickness was calculated by subtracting the elevation of the Mesaverde top from the drill rig Kelly bushing elevation. The resulting isopach map shows the Wasatch thickens from 1,200 feet beneath the southeast corner of the study area to 5,600 to 6,000 beneath the western edge of the study area. The isopach thickness corresponds to the major structural features in the area. The Wasatch is thin over the Divide Creek anticline due to erosion related to uplift, and thickens to the north and west toward the basin axis. In the southeast quadrant of the study area, where the Wasatch is thinnest, there is less separation between shallow water resources and deeper formation waters containing higher major ion and TDS concentrations, as well as petroleum hydrocarbons.

2.3 DELINEATION OF WASATCH UNITS IN THE STUDY AREA

The project scope of work was designed to evaluate potential variations in shallow groundwater quality related to geologic or lithologic conditions in the shallow subsurface, i.e., interconnectedness of sandstone units within a mudstone-dominant stratigraphic column. Given the laterally continuous sandstones of the Molina member described by Donnell (1969), an understanding of stratigraphic correlations between the Molina type section and the study area was desirable. Unfortunately, within the literature there is considerable debate regarding correlation of the Atwell Gulch, Molina, and Shire members at the reference sections of Donnell (1969) to rocks exposed at Rifle Gap (Johnson and Flores 2003, Lorenz 1995 and 1997).

The problem is caused by the absence of a dominant massive sandstone interval on the eastern margin of the basin (e.g., Rifle Gap area) as is seen at the Molina reference section. There is also minimal paleontologic evidence to provide dates or ages within the nonmarine Wasatch Formation, and no other obvious or substantial geologic marker beds to provide correlation horizons. A correlation of the two interpretations from the Molina and Rifle Gap areas, modified from Johnson and Flores (2003), is shown schematically in Figure 2-2.

The study area is situated between these two “classic” outcrop locations and URS is unaware of any attempts by others to correlate the Wasatch units within the area defined for this study. Published geologic maps for the Rifle, Silt, and North Mamm Peak quadrangles do not attempt to identify the three individual members of the Wasatch within the study area. URS geologists visited the Donnell (1969) type section locations briefly with Dr. Larry Jones (Mesa State College professor) in October 2005, and were unable to visually trace the Molina sandstone interval from the town of Molina into the study area along Highway 330, which follows Plateau Creek onto the east flank of Battlement Mesa.

To become familiar with the geology of the study area, URS geologists visited the area several times and studied topographic and geologic maps of the area and LIDAR imagery provided by Bill Barrett Corporation (BBC) to identify sandstone outcrops to measure representative sandstone unit geometries. The sandstone unit geometries (thickness and lateral continuity) were studied in outcrop to provide a conceptual framework to apply to the subsurface when interpreting groundwater chemistry variations between adjacent water wells.

During geologic reconnaissance of the area, URS identified two separate sandstone units that could be traced on outcrop around the Divide Creek anticline and Dry Hollow areas. These sandstone units are interpreted to represent sandstones similar to the Molina member of Donnell (1969), and are described in more detail below.

2.3.1 Molina-Like Member in the Study Area

The most topographically unique sandstone unit in the study area is a yellowish sandstone unit that caps several linear ridges in the eastern half of the study area and appears to be laterally continuous. These ridges are easily discernible on topographic maps, and are located in T7S R92W, Sections 9, 11, 16, 21, 22, 27, and 34). The linear orientation of the ridges changes from north-south in sections 22, 27, and 34, to northeast-southwest in sections 9, 16, and 11. These linear trends are believed to reflect subtle changes in strike and dip related to the structure of the Divide Creek anticline in this area.

A second laterally persistent sandstone unit was identified in the Dry Hollow Creek area, specifically at the Dry Hollow peak or benchmark in T6S 92W, Section 26. URS tentatively correlated sandstone units at this outcrop to the east along Divide Creek, and west along the valley walls of Dry Hollow Creek and Mamm Creek. The trend of these sandstone outcrops reflects the subtle structural trends of the plunging Divide Creek anticline within the southeast portion of the Piceance Basin syncline.

These two large, continuous sands are considered to mark the upper and lower bounds of a sand-rich interval within the Wasatch similar to the Molina or "G" members (see Figure 2-3). Sandstones capping the low sloping ridges surrounding the southeast quadrant of the study area are interpreted to represent the lower portion of the Molina-like member (Wasatch G) of the Wasatch. The Divide Creek measured section (described below) includes at least three sandstone units. Mudstones are interpreted to overlie these sandstone-capped ridges to the north and west. The second sandstone on Dry Hollow is present farther to the north and west, which URS interprets to represent the upper unit of the Molina-like member. The upper unit is represented by the Dry Hollow measured section. The interpreted Molina-like interval in this area is approximately 1,000 feet thick, including the middle mudstone interval.

Assigning these two laterally extensive sandstone units to the "Molina" interval of Donnell (1969), suggests that the rocks located south or below this unit are considered to be the Atwell Gulch member. The section of the Wasatch above this unit to the north and west is considered to represent the Shire member. Because the study area is located on the southeast margin of the Piceance Basin, a regional synclinal feature, rocks exposed at the ground surface generally become younger to the northwest toward the basin axis. Therefore, the oldest bedrock outcrops in the study area are located in the southeast corner (West Divide Creek area), and the youngest formations are exposed in the northwest corner (Grass Mesa area) and southwest corner due to the higher regional elevation to the southwest, exposing younger rocks in the section.

Figure 2-3 is a simplified bedrock geologic map of the study area, showing the interpreted distribution of the three Wasatch members. This designation is supported by estimated unit thicknesses of the interpreted Shire and Atwell Gulch members based on this delineation that are comparable to unit thicknesses observed in cores drilled from Grass Mesa (Johnson and Flores 2003). In addition, below the capping sand of the Divide Creek measured section (section 11 and 12, T7S R92W) is carbonaceous mudstone with intermixed/interfingering sands. This mudstone interval is similar to the upper Paleocene, laterally extensive carbonaceous shales/mudstones below the Molina member along the southwest margin of the basin (Donnell 1969; personal communication Larry Jones). Carbonaceous units can serve as a potential source of natural gas.

Shroba and Scott (USGS 2001) identified a laterally persistent sandstone unit in the Silt quadrangle ("Sandstone Unit of the Shire member"), seen in outcrop about one mile east of the town of Silt and north of the Colorado River and I-70 at Davis Point. URS measured one of the Wasatch outcrop sections for this study at Davis Point because it is the only sandstone unit identified and mapped near the study area. URS then visually correlated sandstone outcrops from the Davis Point area south into the study area into Divide Creek. These sandstone units, or similar sandstone units, are found along the canyon walls of Divide Creek in the northeast corner of the study area, and are also present as resistant ledge-capping units above upper Dry Hollow Creek and West Divide Creek in the southeast portion of the study area. There are at least five topographic ridges in this area that are capped by this sandstone unit. The orientations of these ridges show the outline of the plunging nose of the Divide Creek anticline within the study area. A massive outcrop of sandstone units is also present above Dry Hollow, specifically at the Dry Hollow benchmark in section 26 6S 92W. Sandstone units in outcrop at Dry Hollow can be visually traced laterally to the east into Divide Creek and west and south along the flanks of Middle and East Mamm Creeks.

The upper sand defining the Molina member in the Study Area occupies the same structural and stratigraphic position as the sandstone unit of the Shire member as mapped by Shroba and Scott (1997) and Shroba and Scott (2001) observed at Davis Point, north of the Study area. The base of the Dry Hollow outcrop contains a massive sand, with minimal claystone interbeds that ranges in thickness between 30 to 75 feet in outcrop. This massive sand is traceable in outcrop from Section 20 of T7S, R92E around the nose of the Divide Creek anticline for over 8 miles. Likewise, the yellow sand that caps the Divide Creek outcrop was traced over 7 miles around the nose of the Divide Creek anticline.

Due to the regional strike and dip of the bedrock in the eastern half of the study area, it is difficult to visually correlate individual sandstone outcrops over distances of several miles. URS is uncertain of the exact correlations for individual sandstone outcrops occurring at the Davis Point, Divide Creek, and Dry Hollow areas. URS has chosen to term the laterally persistent sandstone units in the study area the Molina-like unit rather than adopt the terminology of Shroba and Scott (2001). The Sandstone Unit of the Shire member (Shroba and Scott 2001) only consists of two thin sandstone units. It is also located stratigraphically several thousand feet below the top of the Wasatch in the study area, so if it is in the Shire member, then it is in the lower portion of the Shire.

Although the Molina-like sand-rich unit is characterized here as part of the Molina or “G” type sands, it is recognized that it is not intimately related to the type-section at Molina as described by Donnell (1969). Although this sandstone appears to occupy the same approximate stratigraphic position as the Molina member of the Wasatch Formation to the west (i.e., Donnell 1969), the two units demonstrate differences in some sedimentological characteristics and paleoflow indicators of the sandstones compared to the type section (Lorenz and Nadon 2002) and were deposited by stream systems originating from different uplifts (Johnson and Flores 2003). As discussed later in the section on measured sections, URS did not obtain sufficient outcrop measurements of bedding dip directions to evaluate sandstone source areas. This was neither within the scope nor necessary for this study. URS made additional efforts to correlate the laterally persistent sandstone units within the study area for the purpose of evaluating water quality trends in water wells in the areas where these sands are believed to be present in the upper 600 feet (maximum depth of permitted water wells).

URS did not locate any significant outcrops of the Atwell Gulch member, and there is no outcrop within the study area where the contact between the two formations is visible. URS looked for this contact, or the base of the Atwell Gulch member, briefly with Dr. Larry Jones in the region southeast of the study area on the Divide Creek anticline. No sandstone outcrops were identified in this area. In fact, the southeast corner of the study area is devoid of obvious sandstone outcrops. URS has inferred the geology in this area to consist of mudstones comprising the Atwell Gulch member.

There was also no evidence in sandstone outcrops within the study area of volcaniclastic or andesitic clasts or material, suggesting that the coarse-grained intervals of the andesitic unit of the Atwell Gulch member as defined by Shroba and Scott (1997 and 2001) does not exist anywhere within the study area.

2.4 MEASURED SECTIONS

Five stratigraphic sections were measured to evaluate Wasatch sandstone body geometries in the study area. The objective of understanding sandstone body geometries was to use these data to document potential influences of lithologic heterogeneity on water quality data from adjacent water wells. URS obtained landowner permission prior to measuring each section, including other areas where good exposures of sandstones were observed and examined, but complete sections were not measured. Permission to access landowner property was not always granted. A team of three geologists working together on the outcrop measured sections. One geologist measured unit thicknesses using a Jacobs staff and Brunton compass set at a 5-degree dip. Another geologist recorded the group's field observations on field sheets. The third geologist took photographs, marked waypoints with a handheld GPS at many of the lateral breaks or turns in each section, measured bedding strike and dips, and noted grain size, sorting, rounding, mineralogy, and color using a hand lens and scale card. All three geologists were actively involved in making field observations.

The five sections are listed in Table 2-1 and locations of the measured sections are shown in Figure 2-8. All five measured sections were located on slopes facing south or southeast where bedding was exposed. Stratigraphic profiles for each measured section were constructed and are shown in Figures 2-9a through 2-9e. Photomosaics for several of the sections were constructed to show sandstone and mudstone lateral continuity. The photomosaics are included with the measured sections. GPS waypoints for each measured section are provided in Appendix A.

Table 2-1
Summary of Measured Sections

Measured Section	Wasatch Member (URS)	Section Thickness (ft)	Net Sand Thickness (ft)	Maximum Sand/ Mudstone Interval Thickness (ft)	Sand %	Mudstone %	Sandstone Unit Lateral Continuity (visible maximum)*
Davis Point	Molina-like	210	47	20/26	22	78	5,000 ft
Divide Creek	Upper Atwell Gulch Molina-like	466	185	40/55	40	60	6 miles[1]
Dry Hollow	Molina-like	487	110	75/100	23	77	6 miles[1]
Mamm Creek	Shire	575	108	50/124	19	81	3,000 ft
Power Plant	Shire	605	206	70/100	34	66	1,000 ft

Notes: * - Approximate values

[1] – There are breaks in the outcrop continuity caused by weathering, that may obscure depositional breaks in continuity.

The measured sections likely represent thicker sand intervals and thinner mudstone intervals than are typical for the entire area, as the locations were selected in areas where sandstone outcrops are most noticeable. There are a number of study area locations, specifically along the southern and western portion of Grass and Flatiron mesas, where a nearly 1,000-foot section could be measured and very few sandstones would be encountered, as no sandstones are visibly present.

Sandstone units are typically more resistant to weathering processes than the finer-grained mudstones. Sandstone units often occur as steep slopes or cliffs and form a resistant cap on top of ridges, especially in the Divide Creek and Dry Hollow areas. Mudstone intervals are typically on gentler slopes, and may be covered with vegetation. Slopes of mudstone intervals can be quite steep where present immediately below sandstone cliffs. In some locations, the steep mudstone slopes were "hardened" and were difficult to traverse safely.

Measured sections ranged in thickness from 210 to 605 feet. The percentage of sandstone intervals present at each section ranged from 19 (Mamm Creek) to 40 percent (Divide Creek). The maximum thickness of individual sandstone intervals ranged from 20 feet at Davis Point, to 75 feet at the Dry Hollow location. The maximum thickness of an individual mudstone unit in a measured section was 124 feet at the Mamm Creek location. Thicker mudstone units certainly exist within the study area. The measured section locations were selected with the objective of documenting sandstone body geometries.

2.5 LITHOFACIES

URS evaluated the most common mudstone and sandstone lithofacies observed in the measured sections. URS also reviewed approximately 1,200 feet of rock core of the Wasatch Formation that was cut and stored by EnCana from their Moore 33-10A gas well. The gamma, resistivity, and porosity logs for this interval were also provided to URS and reviewed. A total of eight sandstone lithofacies and two mudstone lithofacies were identified at each of the measured section locations. Many of these lithofacies are similar to units described for the Cretaceous-aged Iles Formation near Rangely, Colorado (Anderson 2005 and Caldes 2005). These lithofacies are subdivided primarily by sedimentary structures and grain size. Table 2-2 summarizes the general physical features of the sandstone and mudstone lithofacies. In order of decreasing occurrence in outcrop, for both the sandstone and mudstone, the lithofacies defined by URS are as follows:

- Sandstones
    - Large-scale trough cross-bedded sandstones
    - Planar-bedded sandstone
    - Small-scale trough cross-bedded sandstone
    - Massive sandstone and siltstone
    - Large-scale trough cross-bedded conglomerates
    - Convolute bedded sandstone
    - Ripple cross-stratified sandstone
    - Interbedded thin sandstone and mudstone and coal seams

- Mudstones
    - Red and purple mudstone
    - Gray mudstone

2.6 LITHOFACIES OCCURRENCE AND DEPOSITIONAL SEQUENCES

The scope of work requested the lateral extent of individual lithofacies to be evaluated. As shown on Table 2-2, the estimated lateral continuity of individual lithofacies varies. The lateral extent of individual lithofacies may effect the compartmentalization of the sandstone unit, but not the lateral continuity of the sandstone unit. Table 2-1 shows the estimated lateral continuity of the major sandstone units found in the study area and measured in outcrop.

Each of the sandstone lithofacies described in Table 2-2 was formed by a unique set of depositional processes. A depositional environment can be assigned to each lithofacies, however, the combination of lithofacies present in a rock unit may tell more about the environment of deposition. Gradational contacts between individual lithofacies imply that the two lithofacies environments were adjacent laterally (Walker 1984). The depositional sequence is a three-dimensional assemblage of lithofacies, linked to a modern or ancient model or analogy for the environment of deposition (Fisher and McGowan 1987).

The depositional sequences observed in the Wasatch Formation within the study area are interpreted to have originated in a fluvial environment consisting primarily of channelbelt and floodplain subenvironments. As shown in Table 2-2, the majority of the sandstone lithofacies were deposited in fluvial channelbelts (CB), and the massive sandstone and siltstone lithofacies occurs as crevasse splay and overbank sandstones (OB) within floodplain mudstones (AF). Based upon the width of the sandstone bodies and the pervasiveness of thick mudstone intervals comprising the Wasatch, the Wasatch was deposited in a large alluvial basin, with a number of streams draining uplifted areas where finer-grained unlithified sediments were exposed for erosion.

The thicker sandstone units are interpreted to represent fluvial channel and point bar deposits. The remarkable lateral continuity of the sandstone units in the middle section of the Wasatch has led URS to term this interval the Molina-like sandstone unit, due to the similarity in lateral continuity with the Donnell (1969) reference section. Theories to explain this remarkable continuity of sandstone range from timing of surrounding uplifts (Lorenz 1997), climatic changes (Blecha 2003), and backstripping of the Williams Fork and Mancos Formations during uplift and erosion of the nearby basin margin and subsequent redeposition during Wasatch time (Larry Jones, personal communication, October 2005).

2.6.1 Sandstones

Sandstone units within the study area are typically composed of one or more lithofacies. For example, within the fluvial channelbelt sandstones, seven different lithofacies generally occur within one 20-foot thick sandstone unit, and the contacts between lithofacies are generally gradational in nature (Figure 2-9b 390 feet). In contrast, for the overbank alluvial environment, the massive sandstone and siltstone lithofacies is typically the only sandstone lithofacies present, but occurs interbedded with mudstones (Figure 2-9b 440 feet).

Individual sandstone units are typically comprised of fining-upwards grainsize materials with a basal unit of thinner trough cross-stratified conglomeratic lithofacies that fine upwards to large-scale trough cross-stratified sandstone (Figure 2-9b 106 feet). The conglomeratic unit, where present, is generally scoured from one to as much as 10 feet down into underlying mudstones (Figure 2-9e 170 feet). The basal sand unit is not always conglomeratic, but the basal sand unit typically shows evidence along the outcrop of scouring down into the mudstones. The basal sandstone typically rests unconformably on the gray-colored mudstone facies, and not the red and purple-colored mudstones.

The upper portion of a typical sequence transitions upwards randomly from the small-scale trough cross-bedded lithofacies up to planar-bedded sandstone. The planar-bedded interval is often the thickest lithofacies present (Figure 2-9d 560 feet). Convolute bedded and ripple bedded sandstones, when present, generally occur as discrete units within the upper half of the sandstone sequence. Planar tabular cross-stratified sandstone intervals were rarely seen in outcrop, and are not listed as one of the primary lithofacies.

Reactivation surfaces were commonly observed within the trough cross-stratified lithofacies. These surfaces were identified from cross-cutting relationships between bedsets and the presence of mafic mineral drapes, slightly coarser grain size materials, and poorer sorting at the base of each unit.

Lateral accretion bedding was observed at the Divide Creek, Mamm Creek, and Power Plant section locations. Oftentimes the lateral accretion beds are not obvious while on the outcrop, but are more visible from some distance from the outcrop, or from photomosaics of the outcrop. At the few locations where the lateral accretion bedding was observed on the outcrop, the primary lithofacies observed was large-scale trough cross stratification. Sandstone unit internal geometries of the Molina-like sandstone unit are similar to the “compound sinuous” type C sand bodies of Cole and Cumella (2005).

The interbedded mudstone and sandstone lithofacies was observed in several outcrops, and was associated with the large-scale trough cross-stratified and conglomerate lithofacies. Carbonaceous shale intervals are rare within the measured sections, and typically were only observed within intervals of thinly interbedded mudstone and sandstone. The coal seams were less than one-inch thick, and poorly sorted and coarser sands were present within these intervals. These beds were rarely horizontal or laterally extensive, and likely were deposited within abandoned channels that were subsequently buried by additional channel lag deposits. The abandoned channel features were likely topographic lows on the floodplain that evidently allowed water to pond. Vegetation would grow and organic matter could accumulate in one area between channel avulsion events, forming the thin coal seams.

2.7 MUDSTONE UNIT THICKNESS AND LATERAL CONTINUITY

URS identified three mudstone lithofacies within the study area. The dominant mudstone lithofacies are the gray and multi-colored mudstones. The massive bedded siltstone and sandstone lithofacies is most common in the uppermost 20 to 50 feet below major sandstone units.

The gray mudstones are typically found immediately below major sandstone units. The gray coloration may be attributed to reducing conditions during or post deposition. Reducing conditions could result from the presence of organic material in the mud, prior to the sandstone burying this portion of the floodplain, and depletion of oxygen in the soil due to degradation of the organic material by microorganisms. The gray coloration could also be caused by the presence of standing water and /or poor drainage in the portion of the floodplain overlain by the sandstone. This would be reasonable since the path of the avulsing sandstone channelbelt sequence would likely follow topographic lows. Gray colored paleosols studied by Kraus (1997) in the Lower Eocene Willwood Formation in the Bighorn Basin of Wyoming were attributed to poorly drained areas. Sediment accumulation rates as well as the parent material beneath the paleosols also affected the development of pedofacies.

Kraus (1997) distinguishes between fine-grained avulsion deposits and true overbank deposits based in part on the work of Smith et al. (1989). Avulsion is the process where a fluvial system abandons an established channel and creates a new channel. The distinction is that avulsion begins by crevassing of the trunk channel and development of the crevasse splay. The avulsion channel then progrades through a process of building successively more splay channels. Once the flow becomes concentrated into a single channel in this area, “true overbank” deposition of fine-grained sediments can occur (Kraus 1997).

In the study area, interbedded mudstones and thin, planar-laminated to massive bedded siltstone and sandstones are common, especially within the upper 25 feet of section immediately underlying the larger sandstone intervals. These coarser-grained interbeds generally show massive bedding, likely from bioturbation by organisms. Lateral continuity of these interbeds ranges from 50 to several hundred feet, with thicker units displaying greater continuity in outcrop. This lithofacies is similar to the crevasse splay and associated fine-grained overbank deposits of Kraus (1997). The prograding avulsion-related crevasse splay sandstones and siltstones were not observed beneath every sandstone channelbelt sequence, and a spectrum of avulsion related depositional sequences is likely.

The orange, red, and purple mottled mudstones are extremely prevalent in the measured sections. The rock core from EnCana’s Moore 33-10A well displays vivid colors of red and purple colors with yellow and gold mottling. These mudstones are similar to paleosols described by Kraus (1988, 1997, and 2002), and reflect various stages of paleosol development or maturity. Paleosols are essentially ancient soil profiles, and reflect pedogenic morphologic and geochemical processes occurring after deposition. URS did not evaluate the degree of paleosol maturity or lateral relationships of paleosols at the measured sections. However, the Wasatch outcrops in the study area may provide excellent exposures for other researchers.

2.8 LITHOLOGIC TRENDS ACROSS THE STUDY AREA

Grain size for the sandstone lithofacies are most commonly fine sand with lesser percentages of coarse sand. There is very little material in the granule to gravel size fraction. The coarse-grained material in the conglomerates are almost entirely comprised of subrounded to rounded mudstone rip-up clasts, ranging in size from one to 4 inches. These mudstone clasts were likely derived from channel avulsion and scouring of local alluvial floodplain materials. The lack of gravel and clasts from igneous or metamorphic terrains, especially in the conglomeratic lithofacies (highest depositional energy), suggests the sandstones were deposited some distance from the uplift areas, or the rock materials in the highland areas contained more finer-grained sandstones that were not significantly lithified and could be disaggregated by weathering processes.

Sandstones forming the Molina-like member within the study area evidently thin and pinch-out to the north, as evidenced by the absence of this interval north of the Colorado River on the other side of the Rifle Syncline.

URS estimates that the Wasatch Formation lithology within the study area is comprised of roughly 80 to 90 percent mudstone, and 10 to 20 percent sandstone. Sandstone units in the Atwell Gulch member were typically isolated lenses and were only observed near the base of the Divide Creek section. Sandstone units in the Shire member are typically isolated pods

In the rock core from EnCana's Moore 33-10A well, a number of rock features are easier to see than on the actual outcrop. This includes better exposure of: mottling patterns and colors, root traces, bioturbation, and vertical fractures in the mudstones. These early post-depositional features form macropores in the rock matrix, which often have higher vertical hydraulic conductivities than the surrounding rock. These macropores can provide conduits for vertical movement of water and other fluids. A black-colored silt-filled vertical to sub-vertical fracture was observed in the Moore well core at a depth of 607 to 616 feet. Color zoneation (gray halos) extended into the surrounding red rock matrix from the fracture aperture, indicating movement of fluids with reducing geochemical characteristics migrated within the fracture aperture.

In the Moore well core, coal fragments are rare with rip-up clasts at the base of individual sandstone units. However, sandstones from a depth of approximately 440 feet (no core from 394 to 424 ft) to the top of the core commonly contain small pieces of coal in basal lags of trough-cross stratified sandstones. The sudden appearance of coal fragments at this depth suggests a change in source material for the sandstones. At a depth of about 250 feet, sandstones were observed to contain a large amount of coal rip-up clasts. Above this interval, sandstones have a light gray color, and below this interval, sandstones are "redder" in coloration. URS has interpreted the sandstone interval between approximately 190 to 440 feet in the Moore 33-10A well core to represent a portion of the sandstones of the Molina-like member defined in this study.

2.9 GEOLOGIC STRUCTURE

Task 4 of the scope of work included a request to describe the regional geologic setting including identifying and mapping faults, fractures, and lineaments using geologic maps and satellite/aerial photos and other published data. URS reviewed published literature on the Piceance Basin, including a number of reports referenced in this section, and the geologic maps described earlier. The evaluation of geologic structures was further supported by a lineament analysis completed from satellite imagery and aerial photographs. All of the structural features were placed into GIS shapefiles for use as overlays within ArcMap, where they could be viewed in conjunction with other data in map layers. The identification and analysis of regional and local geologic structures provides useful information for identifying areas where the potential exists for natural gas and deeper groundwater to migrate upwards from underlying reservoirs and impact shallow groundwater or surface water.

A fault is defined as a fracture or fracture zone along which there has been displacement of the sides relative to one another parallel to the fracture. No faults were observed in the field or mapped as part of the lineament analysis. However, numerous fractures and joint patterns were seen in the sandstone units at each outcrop location. Many of the fractures and joints observed on outcrop were likely caused by uplift, erosion, and surface weathering processes. The presence of subsurface fractures or fracture zones in the West Divide Creek seep area may be inferred from the rapid movement of gas from the Schwartz 2-15B well bore. The release of material from this well bore was attributed to a loss of grout into an open fracture system during cementing of the production casing.

2.9.1 Regional Overview

The Piceance Basin is a NW-elongate basin that attained its present configuration as the result of Laramide tectonics. The basin is bounded to the east by the Grand Hogback Monocline, along the north by the Axial Uplift, on the southwest by the Uncompahgre Highlands and separated from the Uinta Basin by the north-south trending Douglas Creek Arch. Much of the following structural history of the area is from Tremain and Tyler (1996).

Although the Piceance Basin was formed during the Laramide Orogeny that occurred during the Late Cretaceous to early Tertiary time period (72 to 40 million years ago [mya]), structural trends displayed during the Laramide were influenced by prior structural trends dating back to the Precambrian. Paleozoic fault orientations reflect the northeast-southwest compression that was believed to have originated in the Precambrian. The Ancestral Rocky Mountains were uplifted during the Pennsylvanian-Permian times and created the Uncompahgre Uplift, the Ancestral Front Range, and the Central Colorado Trough, which separated the two uplifts (DeVoto 1980). The Sevier Orogeny in the northeast portion of the Colorado Plateau caused east-west horizontal compression during deposition of the Cretaceous and early Tertiary sediments (Johnson 1989) between 160 to 72 mya. In late Paleocene, east-west compression shifted to north-south compression (Gries 1983). The Piceance Basin was bounded by uplifts during the Laramide Orogeny. Basin subsidence ceased at the close of the Laramide Orogeny (40 mya), and there was little structural movement or sedimentation until the Colorado River system began cutting deep canyons approximately 10 million years ago (Tremain and Tyler 1996).

The structural axis of the basin is on the east side, adjacent to the Grand Hogback monocline. Numerous, predominantly northwest-trending, anticlines are found within the basin. Southern and eastern portions of the Piceance Basin near the study area are dominated by NW structural trends that were formed by WSW-directed thrusting (Grout et al. 1991; Gunneson et al. 1995).

2.9.2 Anticlines and Synclines

Three major structures traverse the study area, which include the Divide Creek anticline, Rifle-Grand Hogback syncline, and an unnamed syncline (see Figure 2-11). The axis of the unnamed syncline is located west of Grass Mesa, and trends north-northwest to south-southeast. This syncline represents the structural depression between the Divide Creek anticline and the Rulison anticline to the west, which forms the structural framework supporting the Rulison Field petroleum reservoir.

The Divide Creek anticline is a northwest-trending, asymmetrical anticline. It is approximately 15 miles long and 3 miles wide. Figure 2-12 illustrates a schematic interpretation of Divide Creek anticline and related producing fields showing the locations of multiple detachment surfaces interpreted from regional seismic for the central and eastern Piceance Basin (Gunneson et al. 1995). There are two detachment zones shown, one in the basement, and the other in the Mancos Shale. In the interpreted sequence of structural development, the shallower pop-up anticline was decapitated and thrust westward due to later thrusting from the east along detachment at mid-level within the Cretaceous Mancos Shale, leaving the deeper pop-up block to the east. A deeper, basement-involved structure is also present to the east.

The anticline has since been broken up into a series of fault blocks by northeast-trending normal faults that trend orthogonal to the older, northwest-trending thrusts. Structural displacement on these normal faults is relatively small, with maximum displacement of up to 125 feet (Grout et al. 1991). The cross-section depicted in Figure 2-12 is located approximately 1-mile to the southeast of the study area, but the structural geometries depicted are interpreted to reflect the geology beneath the study area.

2.9.3 Joint Sets from the Tertiary Wasatch and Green River Formations

The strike orientations of four sets of joint sets are shown in Figure 2-11. They are labeled F1 through F4, with F1 representing the oldest joint sets. The age of these joint sets is constrained by structural, stratigraphic, and geomorphic evidence and is bracketed by Grout and Verbeek (1992) at 43 to 10 mya old. The F1 joint sets typically strike north-northwest, F2 joint sets strike west-northwest, F3 joint sets strike east-northeast and dominate the southern half of the basin, and the F4 joints strike north-northwest (Tremain and Tyler 1996 and 1997; Grout and Verbeek 1992). The strike of joint sets typically parallel the compressional stress field orientation under which they formed. This suggests that the primary compressional stress direction following deposition and lithification of the Wasatch was east-southeast.

2.9.4 Aeromagnetic Lineaments

An independent aeromagnetic lineament analysis was not conducted for this study. However, data and lineaments interpreted in a previous study by Hoak and Klawitter (1997) were evaluated and further refined for this study. The aeromagnetic lineaments were digitized from regional maps into a GIS shapefile. The interpreted aeromagnetic lineaments are separated into three categories: shallow (short wavelength data), transitional (intermediate wavelength data), and basement (long wavelength data). These lineaments are depicted on Figure 2-11.

There is close correspondence between the location of faults mapped on various structural datums from seismic data (see Figure 2-12) and the linear aeromagnetic anomalies. Northwest-oriented anomalies likely correspond to thrust faults whereas the NE-trending anomalies likely correspond to tear faults or normal faults within the basement structure of the basin. The Divide Creek anticline has been broken up into a series of fault blocks by both northeast-trending normal faults that trend orthogonal to older, northwest-trending thrusts. Structural displacement on these normal faults is relatively short, with maximum displacement of up to 125 feet (Grout et al. 1991). The intersection of normal faults with older thrusts has compartmentalized Mesaverde and Wasatch rocks beneath the Divide Creek throughout the remainder of the study area. The degree in which these faults form seals or provide conduits for natural gas movement is unknown.

The locations of imagery mapped lineaments (surface expressions) in general compare favorably with the linear aeromagnetic anomalies mapped (subsurface expressions). However, there are various regions where the mapped structures do not correspond precisely. Generally, when surficial fracture trends from imagery do not correlate to fracture trends within the basement (i.e., aeromagnetic anomalies), an intermediate depth structural detachment horizon may be present (Hoak and Klawitter 1997). There may be considerable lateral offset observed between the basement fault location and where the fault actually causes a flexure in the shallower stratigraphic units, making it very difficult to establish correlation between basement faults and structures within the shallower reservoirs using aeromagnetics and remote sensing imagery analysis (Hoak and Klawitter 1997).

2.10 LINEAMENT ANALYSIS

Lineaments represent naturally occurring alignments of soil tones, topography, stream channels, vegetation, or combinations of these features apparent on aerial and satellite photographs. Lineaments are assumed to represent faults and areas of intense fracture zones of tectonic origin sufficient enough to conduct fluids. Also, it is assumed that geomorphic expression, such as narrow depressions eroded by stream incision; represent areas preferentially susceptible to mechanical weathering. On terrain covered by recent alluvium, the interpretations of lineaments were based on more subtle criteria such as tonal variations and were presumed to correlate to underlying bedrock structures. With some exception, lineaments are not treated as individual structural elements, but rather, are attributed to a statistical significance on the level of a set of parallel linear grouped elements. Manmade features such as roads/highways and fence lines were noted, but not included in the lineament analysis.

A lineament analysis was completed for the study area and immediately adjacent lands using the high-resolution IKONOS satellite imagery and low altitude aerial photography procured by URS. Mapping was conducted using multiple trials, and retaining the common lineaments of repeated trials similar to the method of Mabee *et al.* (1994). Upon each trial, images were rotated 90° from the previous trial to obtain a dissimilar perspective when annotating the linear features. Additional trials were conducted using different combinations of bandwidths to remove various spatial frequencies and enhance the prominence of the linear features. The use of both aerial photographs and satellite imagery facilitated the ability for a multi-temporal analysis in which the images of the same area were taken from a different year and at a different time of day. This should add a sufficient degree of confidence in the physical reality of recognized lineaments. Interpretations were combined and lineaments uncommon to both interpretations were discarded.

In general, there is good agreement between the orientation of significant trends interpreted from imagery analysis and those determined from ground-based studies (see Grout and Verbeek 1992). This analysis reveals strong preferred fracture orientations and distinct fracture domains defined by internally consistent fracture patterns. These various fracture domains are presumably related to spatial and temporal heterogeneities in the stress field during the development of the fracture systems. Regions that have experienced multiple episodes of tectonic deformation, such as the Rocky Mountains, are a common environment for multiple fracture and faulting patterns, as seen in variations in joint patterns depicted in Figure 2-11. It is tentatively assumed that straight lineaments, which are independent of topography, extend sub-vertically, whereas curvilinear structures are generally assumed to dip less steeply. Alternatively, many of the curvilinear features may represent the surface expression of sand “pods” and/or “amalgamated channels” buried in the shallow subsurface.

It should be noted that the density of lineaments does not always correspond to the degree of structural deformation, but rather the ability in which they can be discerned on aerial and satellite images. For instance, lineaments are virtually non-existent on Hunter Mesa located in the center of the study area, the Colorado River valley, and Grass Mesa. This is attributed to the primary structural features being "masked" by the overlying talus, gravel, and floodplain deposits.

In the eastern half of the study area, the dominant lineament trends are oriented west-northwest to east-southeast and northeast to southwest. These trends are similar to the aeromagnetic anomalies mapped on Figure 2-12. Lineaments in the southwest quadrant of the study area are oriented closer to west to east, and rotate to the northwest to southeast orientation further north in the study area.

Primary lineaments interpreted for this study on the Divide Creek anticline depict orientations that are very comparable to lineaments interpreted from airborne radar (SLAR) data in T8S R91W, located to the immediate southeast of the Study Area and mapped by Tyler et al. (1996).

Table 2-1
Summary of Measured Sections

Measured Section	Wasatch Member or Unit (URS)	Section Thickness (ft)	Net Sand Thickness (ft)	Maximum Sand/ Mudstone Interval Thickness (ft)	Sand %	Mudstone %	Sandstone Unit Lateral Continuity (visible maximum)*
Davis Point	Molina-like	210	47	20/26	22	78	5,000 ft
Divide Creek	Upper Atwell Gulch and Molina-like	466	185	40/55	40	60	6 miles[1]
Dry Hollow	Molina-like	487	110	75/100	23	77	6 miles[1]
Mamm Creek	Shire	575	108	50/124	19	81	3,000 ft
Power Plant	Shire	605	206	70/100	34	66	1,000 ft

Notes: * - Approximate values

[1] – There are breaks in the outcrop continuity caused by weathering, that may obscure depositional breaks in continuity.

Table 2-2
Primary Lithofacies of Sandstone and Mudstone Units

Lithofacies	Sedimentary Structures	Grain Size and Color	Sorting	Depositional Environment Association	Typical Thickness Range	Unit Lateral Continuity (visible maximum)*
Sandstones						
Large-Scale Trough Cross-Bedded Sandstones	Planar tabular bedsets from 1 to 3 feet thick	Medium to coarse, mafic minerals form drapes, light brown	Poorly to moderately well sorted	CB	1 to 6 feet	300 ft
Planar-bedded sandstone	Horizontal planar bedding, can weather to massive unit	Fine to medium, light brown	Moderately well sorted	CB	1 to 10 feet	500 ft
Small-Scale Trough Cross-bedded Sandstone	Planar tabular bedsets less than 1 foot thick	Fine to medium, light brown	Moderately well sorted	CB	0.5 to 3 feet	100 ft
Massive sandstone and siltstone	Structureless, occasionally planar laminated in upper portion, commonly bioturbated	Very fine to fine	Poorly sorted	CS/OB	0.5 to 3 feet	200 ft
Large-Scale Trough Cross-Bedded Conglomerates	Festoon cross-bedding, scour or erosive base, mudstone rip-up clasts common	Coarse sand with mudstone clasts up to 2 inches in diameter, medium to dark brown	Very poorly sorted	CB	0.5 to 4 feet	100 ft
Convolute bedded sandstone	Convoluted and diapiric bedding	Fine to medium, light brown	Moderately well sorted	CB	1 to 3 feet	20 ft
Ripple Cross-stratified sandstone	Horizontal planar ripple bedding	Very fine to fine, light brown	Moderately well sorted	CB	0.5 to 1 foot	20 ft
Interbedded thin sandstone and mudstone and coal seams	Massive sandstones less than 0.5 feet thick, sand seams, gray mudstone seams, coal seams	Very fine to fine sand, shale is dark brown to black	Poorly sorted	AC	1 to 3 feet	50 ft

Table 2-2
Primary Lithofacies of Sandstone and Mudstone Units

Lithofacies	Sedimentary Structures	Grain Size and Color	Sorting	Depositional Environment Association	Typical Thickness Range	Unit Lateral Continuity (visible maximum)*
Mudstones						
Red and purple mudstone	Yellowish orange to gold-colored mottling, root traces, burrows, thin massive-bedded siltstone units with concentric weathering, high-angle conjugate fracture sets	Silt and clay, orange, red, or purple	NA	OB	1 to 50 feet	1,000 ft
Gray mudstone	Yellowish-orange to brown mottles, high-angle conjugate fracture sets	Silt and clay, gray	NA	OB	0.5 to 20 feet	1,000 ft

* - Estimated continuity
CB – Channel belt sequence
AC – Abandoned channel fill
CS – Crevasse splay
OB – Overbank deposit

This section of the report describes the hydrogeologic conditions for the alluvial and bedrock aquifers within the study area. This discussion includes the data sources available for evaluation, the distribution of the two aquifer types, information on the permitted wells completed within each aquifer, and a description of the aquifer properties, including depth to water, specific capacity and aquifer hydraulic conductivity. A potentiometric surface map for the Wasatch Formation aquifer was constructed from existing data and is used to evaluate the direction of groundwater flow beneath the study area.

3.1 HYDROLOGIC DATA SOURCES AND COMPILATION

The following sources were reviewed to obtain hydrologic data on the Wasatch Formation and water wells within the study area:

- The State Engineers Office (SEO) for information on permitted water wells, both electronic and paper data
- United States Geological Survey (USGS)
- U.S. Environmental Protection Agency (USEPA)
- Colorado Department of Public Health and Environment (CDPHE)
- Mesa State College; and
- Local water well drillers

Based upon our review of these data, there were approximately 932 permit numbers for wells in the Phase I study area. URS compiled available water well information regarding wells completed in both the alluvial aquifers and Tertiary Wasatch (Tw) Formation.. All the Alluvial and Wasatch wells are identified on Figure 3-1.

The Colorado SEO provided a CD-ROM to URS that contained available database records for water wells permitted in the study area of Garfield County. All of the existing data provided from the SEO was in a Microsoft Access database (WELLS.DBF) file. This information is updated quarterly by the SEO. This database contains a limited amount of information regarding individual wells. Most of the information is regarding dates and status for permit requests and permit authorizations.. There is essentially no lithologic information within the Microsoft Access database file (WELLS.DBF). To achieve the objectives of the scope of work, URS needed information describing the lithologic materials encountered at each water well, especially within the screened or perforated interval. The lithologic information needed for this project was obtained from the drillers logs that had to be reviewed individually.

The lithologic information obtained during well installation and completion is provided to the SEO on a Well Construction and Test Report, or water well driller log. These driller logs are submitted as paper forms, and then scanned by the SEO. URS requested an electronic version of all of the scanned “receipts”, or correspondence, from the SEO in July 2005 and these data were provided. These scanned receipts contain copies of all of the correspondence on file for individual wells within the study area. There were more than 6,000 individual scanned documents in this file. There are approximately 1,008 receipt numbers in this database, with an average of six image files per receipt number. The image files are not uniquely named, so every record had to be opened electronically to identify the water well driller log. Copies of the drillers log were made.

The driller logs contain information regarding the Owner, the location in quarter-quarter section and township and range, drilling methods, total depth, hole diameter, casing types and lengths, screened intervals, a geologic log, and well test data. URS geologists reviewed the driller logs for 453 permitted water wells and entered the information into a separate database (SEODrillLog.DBF) developed by URS and linked to the SEO well or receipts database.

The water well driller logs contained information covering a span of almost 45 years of well installations within the study area. Logs for 451 permitted wells were identified and reviewed. The number of wells completed for specific time periods are listed below. The total number of well completions has increased each decade, reflecting population increases in the area over the same time periods.

- 1963-1970: 18 wells
- 1970-1980: 47 wells
- 1980-1990: 122 wells
- 1990-2000: 161 wells
- 2000-2005 (through April): 90 wells

The water well logs were reviewed for completeness and the quality of the geologic descriptions was entered into the SEODrillLog.DBF file. There were 311 geologic logs noted as Poor, 109 logs interpreted as Good, and only 17 Excellent geologic logs. The electronic well permit records were linked electronically in the Access database, allowing more rapid access to the paper copies. Complete information was available for only a relatively few wells. However, there was sufficient data available within the entire database to provide a basis for this broad-based study.

Lithologic information for 430 permitted wells was available. The geologic logs for a large number of wells (190) did not provide any lithologic description other than “Wasatch Formation”. Some of the most useful information was the depth of the “first observed water” and the well test data completed when the pump was installed. The depth of the first observed water is the best indication of where the water was initially located in the subsurface. The static water level noted at the beginning of the well test was utilized for the potentiometric surface map of the Wasatch Formation presented in a later section. The production flow rate and final pumping level were used to calculate specific capacity at each well, which was in turn used to infer hydraulic conductivity. Well tests were performed on 398 permitted water wells.

URS reviewed the driller logs to evaluate if an individual well was completed in the Wasatch aquifer, an alluvial aquifer, or screened in both aquifers. Figure 3-1 shows the locations of water wells from the SEO database. The number of wells completed in each aquifer is shown below:

- Alluvial aquifer: 48 wells
- Wasatch aquifer: 388 wells
- Both aquifers (Al and Tw): 5 wells
- Unidentified or incomplete log: 9 wells

Rotary drilling methods (primarily air rotary) were used for 309 water well completions, and cable tool methods were used for 73 well completions in the study area.

One problem encountered by URS was correlation of many of the SEO water well locations and the GPS coordinate based locations for water quality samples. Tying these two data sets together was determined to be beyond the scope and schedule of this project.

3.1.1 Stream Gauging Data

A search was conducted using available United States Geological Survey (USGS) National Water Information System to determine locations of surface water gauging stations in the study area. There appear to be no USGS or United States Bureau of Reclamation (BOR) surface water gauging stations in the study area. The search included USGS or BOR Agency Code number, site number, USGS or BOR station number, and daily mean stream flow in cubic-feet per-second. There were several USGS and one BOR gauging stations located on nearby creeks, but all were located outside the study area. Calculations of base flow in study area streams and creeks were therefore not conducted by URS during this initial project phase.

The two closest stations maintained by the USGS are on Beaver Creek (USGS Station 09092500, Latitude 39°28'19", Longitude 107°49'55" NAD27, Garfield County, Colorado, Hydrologic Unit 14010005) and at Raven above West Divide Creek (USGS Station 09089500, Latitude 39°19'52", Longitude 107°34'46" NAD27, Mesa County, Colorado, Hydrologic Unit 14010005). Beaver Creek is located immediately west of the study area, and a short stretch of Beaver Creek actually abuts the southeast corner of the study area boundary for a short distance. The Raven station is located in Mesa County, approximately 5 miles to the south from the southeast corner of the study area up West Divide Creek. Both stream flow and water quality data are available for these two stations. A USGS stream gauge was also operated on East Divide Creek near Silt between 1960 and 1965.

3.2 AQUIFER DEFINITION

There are two types of aquifers in the study area, alluvial and bedrock. Alluvial aquifers consist of saturated sediments that occur in stream valleys and are typically in hydraulic connection with the adjacent stream. The bedrock aquifer within the study area consists of the Wasatch Formation. The Wasatch extends from ground surface to a minimum of about 1,200 feet bgs (maximum of about 6,000 ft bgs), and the deepest water wells are approximately 600 feet deep in the study area.

3.3 BASIS FOR ESTIMATION OF SPECIFIC CAPACITY

Specific capacity was estimated from well testing completed during pump installation. The driller installs a pump in the well and pumps at a steady rate for a set period of time (typically 2 hours). This rate is believed to be the sustained yield for the well. Often a rate of 15 gallons per minute (gpm) is used as this is the highest permitted pumping rate for most domestic wells. The static water level is measured prior to the test, and a final water level is measured after pumping at the sustainable rate for a specific number of hours.

Specific capacity is calculated by dividing the pumping rate by the amount of drawdown observed during the test, and is express in units of gallons per minute per foot of drawdown.

Specific capacity varies with duration of pumping, such that with an increase in pumping time there is a decrease in specific capacity. The specific capacity of a well is typically constant at a given pumping rate as long as the aquifer does not go dry or is not dewatered (Driscoll 1986). Domestic wells were tested by the pump installer using a bailer of a specific volume (usually 5 or 10 gallons), an electric submersible downhole pump, or by using compressed air to lift the water from the well. URS identified a total of 349 water wells that had complete pump test information prior to final well completion from both the alluvial and Wasatch aquifers.

Specific capacity can be used to estimate hydraulic conductivity or permeability of the aquifer materials. However, the water level measurements used to estimate specific capacity are of questionable quality and only suitable for qualitative analysis. Specifically, many of the final water levels were noted as “Total”, indicating the water level was pumped down to the top of the pump during the test. Typically the pump is not located at the very bottom of the well; so URS assumed that the pump was located 10 feet above the bottom of each well and used this depth when the driller or pump installer did not note a depth for the final water level. “Total” was used for the final water level designation for 119 pump tests in the study area. In addition, specific capacity generally declines as the duration of the pumping test increases. The pumping tests conducted during pump installation activities would be considered a short-term test. Therefore, using these data may not be a reliable way to predict long-term performance of individual wells.

For several water wells drilled by the same contractor, the driller measurements indicated identical static and final water level depths. These wells were pumped at relatively high flow rates, suggesting they could have higher specific capacity values. However, specific capacity values calculated for zero net drawdown are unrealistically high if the static water level and final water level are identical. URS compensated for this by setting the final water level one foot deeper than the static water level for all tests where the two levels were identical. These data could have been excluded from the analysis, but they were judged to be representative of higher yield wells. The pumping rates maintained during these few tests were relatively high as compared to other tests.

A typical single-family household needs approximately 300 gallons per day (gpd) for combined indoor and outdoor uses. To produce this rate of water from a domestic well requires a steady, long-term pumping rate of approximately 0.2 gallons per minute. URS estimated the specific capacity necessary to provide this rate of flow based on several assumptions. A long-term duration pumping test with a specific capacity value of 0.04 gpm/ft, with 10 feet of available drawdown, and a safety factor of 0.5 would yield 0.2 gpm or 300 gpd (0.04gpm/ft*10ft*0.5=0.2gpm). Of the 340 wells “tested”, 108 wells (32 percent), primarily bedrock wells, had specific capacity values below 0.04 gpm/ft. This suggests that sufficient well yield is likely an issue of concern for many residents within the study area.

URS evaluated the available data for mapping of hydraulic conductivity and found the data available for the study area inadequate for preparing a meaningful map of this parameter. Hydraulic conductivity, or coefficient of permeability, is the capacity of a porous media to conduct water (Driscoll, 1986). Hydraulic conductivity is tied to the size, shape and interconnection of the pore spaces in granular (alluvial) aquifers, and fracture aperture width and continuity in fractured rock (bedrock) aquifers, and the density, viscosity, and temperature of the water. Bedrock aquifers can also have granular or matrix porosity, especially for sedimentary rocks (i.e. sandstones). However, the Wasatch rocks observed in outcrop, both mudstones and sandstones, seem to have relatively low matrix porosity that would likely yield little water to a well. URS interprets the Wasatch wells where yields are more substantial to be caused by groundwater flow within fractures.

URS had originally proposed to use specific capacity values to derive empirical estimates of hydraulic conductivity (Walton 1962). Unfortunately, the accuracy and reliability of the static and final water level measurements from the driller logs seems insufficient for more than estimation of specific capacity. There is no longer term aquifer pumping test data to allow an initial estimate of hydraulic conductivity upon which to base an empirical relationship, therefore, no estimates of hydraulic conductivity were calculated as part of this Phase I study. However, a map of specific capacity values was prepared to illustrate spatial trends in productivity of the aquifer, as discussed below in Section 3.5.

3.4 ALLUVIAL AQUIFER EVALUATION

Alluvial aquifers for this study are defined as saturated unconsolidated sediments deposited in river valleys that are in hydraulic connection with modern steam systems. The water table intersects the stream channel, and groundwater within these aquifers exists under unconfined conditions. Groundwater and surface water interact, and streams may be considered gaining or losing depending upon whether water groundwater flows into the stream (gaining) or if the stream loses surface water to the aquifer (losing stream). Streams may alternate between gaining and losing seasonally during the year.

Locations of surface water features, including rivers, streams, lakes, ponds and springs were utilized as a GIS mapping layer to identify surface water sources in the study area. There are several alluvial aquifers within the study area, which are present along existing stream valleys. The streams of sufficient flow volume and stream valley size to host an alluvial aquifer capable of providing groundwater for a domestic well are the:

- Colorado River
- Dry Creek
- Mamm Creek
- Dry Hollow Creek
- West Divide Creek
- East Divide Creek, and
- Divide Creek

Based on review of driller logs and the map shown in Figure 3-1, the majority of the alluvial water well completions in the study area are within the Colorado River valley alluvium. Groundwater within alluvium in each river valley, is not hydraulically connected to other stream systems. One exception could be the Colorado River alluvial aquifer, which receives groundwater from each of the separate alluvial aquifers in the study area.

URS found that many of the available well logs lack the information needed to distinguish alluvial from bedrock water wells. The SEO database does not distinguish alluvial from bedrock water wells in the study area. URS reviewed the water well driller logs for indications of whether the wells were completed within unconsolidated or consolidated (Wasatch bedrock) materials. Oftentimes the drillers lithologic descriptions are insufficient to determine the origin of the sediments. URS considered the physical location of the water well and total depth of the well, in addition to the drillers lithologic descriptions. However, the SEO database only provides locations to the nearest quarter-quarter section and amore exact (i.e., GPS) location would be helpful to ascertain a water well location proximity relative to a stream valley. Therefore, a determination of whether a well was completed in alluvium or bedrock could not always be made.

A total of 48 possible alluvial aquifer water wells were identified within the study area. Figure 3-1 shows the locations of alluvial and bedrock water wells in the study area. Approximately 15 water wells identified as Wasatch wells on Figure 3-1 may be alluvial well completions. The identification of alluvial versus bedrock water wells within stream valleys is in some cases only an educated guess. With additional investigation (i.e. visiting the well, measuring the total depth, and obtaining GPS coordinates, or in some cases calling the well owner) the accuracy of this determination could be improved. Table 3-1 summarizes the well completion data for permitted wells that URS has identified as completed in alluvium.

Table 3-1
Alluvial Aquifer Well Completion Summary

	Number of Wells	Screen Length Mean (ft)	Total Depth Range and Mean (ft)	Depth to Water Range and Mean (ft)	Static Depth to Water Range and Mean (ft)
All Alluvial Wells	48	5-35 / 17	12–100 / 60	8–73 / 42	1-81 / 30

The alluvial water wells are shallower than the bedrock wells, with a mean depth of 60 feet bgs, and screen lengths are correspondingly shorter. Figure 3-2 is a histogram showing the total depths of alluvial and bedrock water wells. There is less variation in the total depth of alluvial water wells than for the bedrock wells. Several wells are screened across alluvium and the underlying Wasatch bedrock. Based on the higher permeability of the alluvial sediments, most of the water produced from these wells is believed to come from the alluvial aquifer.

Review of driller logs indicated that first water was observed during drilling between 8 and 73 feet bgs, and that static water levels in completed wells are shallower, with a mean depth of 30 feet bgs.

The recharge to alluvial groundwater is mainly from local and sub-regional rain or snow precipitation events and associated runoff, causing elevated stream flows. Irrigation return flow is likely a local source of recharge to the alluvial aquifers. The alluvial aquifer in the Colorado River alluvium is also recharged directly from bank recharges from elevated Colorado River surface water levels that occur during flood or high water events. Other surface water bodies located within river valleys, including springs and ponds, probably also recharge alluvial aquifers.

Specific capacity (in gallons/minute/ft drawdown) was calculated for 37 alluvial aquifer wells using hydraulic well testing information. This analysis was also completed on 304 Wasatch aquifer wells. Table 3-2 shows the results of these calculations:

	Alluvial Aquifer	Wasatch Aquifer
Mean Specific Capacity	7.3 gpm/ft	25 gpm/ft
Median Specific Capacity Value	2.2 gpm/ft	0.009 gpm/ft
Minimum Specific Capacity	0.0274 gpm/ft	0.0004 gpm/ft
Maximum Specific Capacity	50 gpm/ft	555 gpm/ft
Minimum Pumping Rate	1.5 gpm	0.08 gpm
Maximum Pumping Rate	50 gpm	80 gpm
Median Pumping Rate	19.5 gpm	9.5 gpm

As compared to bedrock wells, the alluvial aquifer wells have higher median specific capacities (2.2 gpm/ft versus 0.009 gpm/ft for bedrock wells) and higher median pumping rates (19.5 gpm versus 9.5 gpm for bedrock wells). This is not surprising since the alluvial aquifer generally consists of coarser, unconsolidated sediments that should result in higher values of hydraulic conductivity compared to the finer-grained and cemented materials comprising the bedrock aquifers. The majority of groundwater flow within the bedrock aquifer is likely due to fracture flow, and would be greater in areas with higher fracture density.

Table 3-3 is a histogram of specific capacity for alluvial and Wasatch wells. Figure 3-4 is a map of specific capacity for alluvial and Wasatch wells. Alluvial wells are shown with open circles. Many of the alluvial wells completed in the Colorado River alluvium display specific capacity values above 1 gpm/ft of drawdown. Several of the wells shown along the south edge of the Colorado River valley and designated as Wasatch wells may be alluvial wells, but the driller logs identified bedrock or Wasatch materials.

Of the 48 alluvial aquifer wells, only 38 wells had water level data available. The wells generally occur in clusters within the different stream valleys, and the data does not lend itself to contouring in a meaningful manner. Therefore, URS did not develop a potentiometric surface map for the alluvial aquifer for the study area during this phase of the project. However, given the linear nature and downstream orientation of the alluvial aquifers, the groundwater flow direction within each alluvial aquifer is probably oriented downstream, subparallel to the stream orientation.

3.5 WASATCH FORMATION AQUIFER CHARACTERISTICS

This section describes hydrologic conditions for water wells screened within bedrock. Within the study area, water wells are either completed in alluvial (unconsolidated) materials or bedrock. Bedrock well completions are screened in the Wasatch Formation, since it is the predominant bedrock present at the ground surface throughout the entire study area. The one exception is the southwest corner of the study area, where the Green River Formation is present. However, there are no water well completions in this area. Since the maximum water well depth is 600 feet, and the Wasatch extends to a minimum depth of 1,200 feet below the ground surface, all of the bedrock water wells in the study area are completed in the Wasatch Formation.

The Wasatch Formation in the study area consists predominately of very fine-grained mudstones with lenses of generally very fine to coarse-grained sandstones. The resulting rock matrix is inferred to have a low porosity and relatively low hydraulic conductivity, or ability to transmit water. Groundwater produced in domestic water wells screened in the bedrock is most likely produced from groundwater flow within fractures with a minimal contribution from the rock matrix. The most productive water wells would be wells completed in areas with the greatest number of interconnected bedrock fractures. The greatest number of bedrock fractures is anticipated to occur in areas where the greatest structural displacements have occurred during the time period since the Wasatch was deposited, beginning in the mid to late Eocene.

The SEO water well database does not reliably distinguish alluvial from bedrock water wells in the study area, and the majority of the wells in the study area are listed with an aquifer designation of "GW, or all unnamed aquifers". URS reviewed the water well driller logs for indications of whether the wells were completed within unconsolidated or consolidated (Wasatch bedrock) materials. The physical location of the water well and total depth of the well were also considered as part of this review. The uncertainty in determining the aquifer type is highest in relatively shallow water wells (100 feet or less) adjacent to stream valleys, especially near the Colorado River.

A total of 388 Wasatch aquifer water wells were identified by URS within the study area. Figure 3-1 shows the locations of the bedrock water wells in the study area. Table 3-3 summarizes the well completion data for permitted wells that URS has identified as completed in the Wasatch.

Table 3-3
Wasatch Aquifer Well Completion Summary

	Number of Wells	Screen Length Range and Mean (ft)	Total Depth Range and Mean (ft)	Depth to Water Range and Mean (ft)	Static Depth to Water Range and Mean (ft)
All Wasatch Wells	388	14-440 / 48	32-600 / 200	3-488 / 107	0-342 / 73

Based upon review of driller logs, there are approximately ten times more water wells completed in the Wasatch bedrock than in the alluvial aquifers (388 versus 38). In general, Wasatch wells are deeper (200 feet versus 59 feet for alluvial wells) and have longer screen intervals (48 feet versus 17 feet for alluvial wells) than the alluvial wells. The depth to first observed water is deeper (107 feet versus 42 feet for alluvial wells) and the depth to static water is also deeper (73 feet versus 30 feet for alluvial wells).

Specific capacity estimates and pumping rate data are summarized in Table 3-2. In general, both the median specific capacity and pumping rate values are lower for bedrock wells than for alluvial wells. 34 percent of Wasatch wells have specific capacity values less than 0.04 gpm/ft compared to 3 percent for alluvial wells. This data suggests that approximately one in every four wells completed in the bedrock aquifer may have poor yields for a typical household. Figure 3-3 is a histogram showing the distribution of specific capacity values for alluvial and Wasatch well completions.

The estimated values of specific capacity for Wasatch wells were plotted against total depth of the well and are shown in Figure 3-4. The general trend of the graph shows that specific capacity is highest for bedrock wells completed at depths of about 100 feet bgs. Specific capacity tends to decrease with well depth, as expected, based on increased lithostatic and confining pressures with depth.

There are multiple Wasatch water well locations that exhibit relatively high specific capacities located across the study area. Figure 3-5 is a map of calculated specific capacities for alluvial and Wasatch well completions. The higher values are depicted by large red dots. Several of the wells with higher specific capacity values occur in areas of roughly conjugate trends oriented northwest-southeast and northeast-southwest. These structural trends are subparallel to aeromagnetic anomaly features interpreted by Hoak and Klawitter (1997). Many of the wells with higher specific capacity values are located in the Dry Hollow area where the well completion may intersect the Molina-like sandstone and the sandstones may be fractured. URS has interpreted the higher specific capacity values to be likely caused by water well completions that intersect a greater number of subsurface fractures.

There are three regions where the distribution of water wells with elevated specific capacity values suggest areas of greater fracture density and higher groundwater yield:

- Dry Hollow Creek, east-west trend, near Sections 3 and 4 of T7S R92W, and Sections 33 and 34 of T6S R92W
- West Mamm Creek and Hunter Mesa, northeast-southwest trend, Sections 29 and 14 of T7S 93S and Sections 31 and 32 of T6S 92S
- Grass Mesa, northwest-southeast trend, Sections 27, 34, and 35 of T6S 93W

The Dry Hollow Creek trend contains some of the highest specific capacity values calculated within the study area. This area is located on the plunging nose of the Divide Creek anticline. The Molina-like sandstone member also underlies this area. The Molina-like sandstone member is also present in other areas along the east third of the study area, many of which have low specific capacity values (Figure 3-5). Wells with higher specific capacity values in this area may result from a combination of sandstone well completions in an area with increased fracture density.

The West Mamm Creek and Hunter Mesa wells with higher specific capacity are also interpreted to coincide with a pair of northeast-southwest trending aeromagnetic anomalies. There are relatively few water wells completed in the Hunter Mesa Area, but the majority of wells completed in the southwest half of this area (near West Mamm Creek) exhibit above average specific capacities.

There are four water wells in the Grass Mesa area with high specific capacity values. Two are on Grass Mesa, and two are located on the east side of Grass Mesa. These well locations coincide with a northwest-southeast trending aeromagnetic anomaly mapped in this area. Other evidence of groundwater occurrence related to this structural trend is the presence of two springs located on the east slope just below the top of the mesa. The springs are identified on the USGS topographic map for this area, and are located immediately north of the aeromagnetic anomaly in this area. The springs are interpreted to result from fracturing of the Wasatch Formation in this area, causing groundwater to discharge at the springs. This groundwater could originate from a shallow perched horizon 20 to 40 feet deep, or from the deeper water table that is located approximately 130 feet below the ground surface in this area.

The comparison of basement linear features and calculated specific capacity data suggests that wells with elevated specific capacity have a tendency to occur along the strike of documented regional aeromagnetic lineaments and surface lineaments. This is probably caused by an increase in the number of subsurface fractures in both mudstone and sandstone units of the Wasatch, which provide conduits for groundwater movement. The location of a water well completion in relation to the Molina-like sandstone member of this study may also contribute to increased specific capacity in fracture zones. Similar correlations have been noted between the regional aeromagnetic lineaments and groundwater geochemistry results (see Section 5).

3.5.1 Potentiometric Surface and Groundwater Flow Directions

Figure 3-6 is a potentiometric water surface map of the Wasatch bedrock aquifer within the study area. The water level elevations were calculated from static water levels obtained during pump installation testing and recorded on driller logs. The static water levels are from water wells installed between 1966 and 2005. The depths measured to static water can only be regarded as approximate given the range of dates they were obtained and unknown pumping conditions at their time of measurement. Depths to water range from 20 feet bgs in the southeast corner to 30 feet bgs in the northeast corner and about 120 feet bgs up on Grass Mesa.

Ground surface elevations were calculated using the GIS and the digital elevation model for the area. The contours were created by best-honoring the actual water level elevations, calculating the local depth to water and extrapolating along the ground surface elevation to the next data point. This method serves to honor the existing water level data and follow ground surface topography.

Groundwater flow typically occurs from higher to lower topographic elevations, which in the study area is from south (flanks of Battlement Mesa) to north (Colorado River valley). Potentiometric surface lows extend up the narrower reaches of stream valleys, and highs extend or bow down the mesas. Groundwater highs are also present beneath the broad upland areas, specifically Hunter Mesa located in the center of the study area and the upper Dry Hollow and West Divide Creek region located in the southeast corner of the study area. The contour patterns suggest that mesas and other elevated areas are generally areas of recharge, and the steams are discharge areas. The ultimate discharge area for groundwater derived from the study area is the alluvium in the Colorado River valley. Groundwater flow in the Colorado River valley is from east to west. The recharge to bedrock groundwater is likely from local and sub-regional rain or snow precipitation events and irrigation water return flow. The recharge from streams within the study area is likely low, based on the potentiometric surface map. There are very few ponds or reservoirs within the study area, although locally these surface water bodies may recharge the bedrock aquifer.

Hydraulic gradients vary and generally reflect topographic gradients. In the southeast quadrant of the study area, the hydraulic gradient is 0.022 feet per foot (ft/ft) with groundwater flow predominately to the north. To the south, the rise in the ground surface elevation caused by the Dry Hollow hill area (section 26 T6S R92W) divides the groundwater flow to the northeast Divide Creek) and northwest (Dry Hollow Gulch). Beneath Hunter Mesa, in the central region of the study area, hydraulic gradients range from 0.042 ft/ft in the upper reaches to 0.028 ft/ft in the lower portion. On Grass Mesa, the hydraulic gradient is approximately 0.048 ft/ft beneath the southern half, and becomes steeper to the north (0.061 ft/ft). Beneath Taughenbaugh Mesa the hydraulic gradient is approximately 0.05 ft/ft. The gentlest hydraulic gradient is 0.011 ft/ft measured along the Colorado River valley. The steepest hydraulic gradients are beneath the steep east flanks of Grass Mesa, and may be as high as 0.188 ft/ft.

3.5.2 Artesian Conditions

URS located and reviewed one published report that describes hydrodynamic conditions for the Williams Fork Formation in the Piceance Basin (Kaiser and Scott 1996). The Williams Fork is the primary gas reservoir in the Mesaverde beneath the study area. Fluids within the Williams Fork Formation in the Piceance Basin are generally overpressured, which means the pressure gradient is greater than the typical hydrostatic gradient of 0.433 pounds per square inch per foot of depth (psi/ft). The higher pressure within the gas reservoir indicates that wells completed in the Williams Fork and left open at the ground surface would be artesian, and deeper groundwater, and hydrocarbons if present, would flow from the open pipe due to the underlying pressure in the formation. An old gas well located in Section 36 T7S R92W was inadequately plugged in 1966. The landowner called the COGCC in 1993 to report leakage of water and oil near his irrigation ditch and to obtain assistance in plugging the well.

There is an abandoned gas well located on National Forest land near Uncle Bob Mountain that discharges freely into Clear Creek. This older well has not been completely plugged because Forest Service personnel have wanted the discharged water for wildlife use. The water discharged has a relatively high conductivity, which is anticipated for deeper groundwater from the Williams Fork.

URS was told by both the COGCC and a water well driller that an area of artesian pressure exists in Section 9 of T7S R92W. Evidently a sandstone unit located at a depth of about 2,000 ft bgs has high water pressure and requires gas well drillers to weight-up the drilling mud when this interval is encountered while drilling.

4.1 GAS WELLS DRILLING DATA

Data evaluated for this discussion were compiled from several sources including the Colorado Oil and Gas Conservation Commission (COGCC), EnCana, and Bill Barrett Corporation (BBC). The COGCC data were provided in an electronic Access database last updated September 2005. The database contained information related to the natural gas development activities and water quality data. Based on our review, data was provided for 1, 353 oil and gas wells including abandoned locations and permitted and planned well locations. General information within the electronic database pertaining to well API numbers, facility numbers, well names, well status, operators, and well surface coordinates was complete or nearly complete. The COGCC on-line database was also searched for detailed records on a select number of wells. Like the SEO water well database, this on-line database contains a large amount of information in the form of scanned paper documents that are not included in the electronic database. Although some of the data missing from the database can be found in electronic documents housed on the on-line database, some of the records are incomplete, as the data is not reported to the state (i.e. mud weights). Given the number of gas wells in the study area, there is also too large a volume of scanned documents (10's of thousands) within the on-line database to efficiently access all of the information. URS also requested and received well bradenhead pressure data from the COGCC. Additional information regarding formation tops, the top of gas occurrence, and well bottom hole coordinates was solicited from EnCana and Bill Barrett Company to more cost-effectively obtain the data that was also available in the on-line database. Much of this information was received and utilized in a Petra data management and mapping software format.

4.1.1 Data Evaluation for Potential Gas Well Problems

The data were reviewed from the perspective of activities associated with well drilling, completion, and production that could potentially impact surface and groundwater resources. There are several areas that are important:

- Integrity of the cementing job
- Height of cement above the top of gas
- Production casing integrity
- Depth of surface casing relative to depth of potable water
- Integrity of surface casing cement job
- Perforation and frac intervals and procedures
- Presence of significant subsurface fracture zones
- Bradenhead pressure measurements
- Well plugging and abandonment

Typically, a substantial interval of the annular space outside the production casing is not sealed with cement. There is no cement in the region located below the base of the surface casing down to the top of the cement used to seal the production (perforated) interval. Within this uncemented interval, gas pressure, if any, will be monitored at the wellhead as bradenhead pressure.

However, if a gas well production casing is adequately cemented to a height above the top of known gas occurrence, and the cement retains it's structural integrity during the perforation and frac completion activities, then there should be no leakage of gas or other fluids into or up the annulus.

If the cement does not extend above the depth of the uppermost gas occurrence, gas can flow into the wellbore and up the annulus. This gas, if present at sufficient pressure, can enter potable water supplies if the depth of the surface casing and cement does not extend below the water-bearing zone. This gas can also leave the wellbore and flow out into the surrounding formation, either through permeability within the rock matrix and/or along fractures that intersect the annulus.

At the Schwartz 10-2B well, a faulty cement job allowed gas and associated hydrocarbons to migrate over 2,000 feet southeast of the well, evidently along a fracture system, and seep into West Divide Creek. The failure of the cement job was attributed to an underpressured zone or a natural fault or fracture.

4.2 HISTORY OF DEVELOPMENT

Oil and gas exploration in the study area began in 1959 with the drilling of the Starbuck #1. The well is located in the southeast portion of the study area in the northwest quarter of the northwest quarter (NWNW) Section 25, T7S, R92W. Mountain States Drilling drilled the well on the Divide Creek anticline to a total depth of 5,710 feet. Gas was recovered during drill stem tests (DST) from intervals at 2,798 to 2,900 feet and 3,675 to 3,750 feet. Casing was set and several zones were perforated from 3,000 feet to 5,560 feet. During initial testing the well flowed gas at an estimated rate of 500,000 cubic feet (MCF) per day, but was subsequently plugged and abandoned in July 1959.

Only 23 gas wells were drilled prior to 1994, and 8 of these wells are still listed as producing. The oldest producing well in the area is the Koch-Mobil 11-20, completed in June 1982 (NESW Sec 20 6S 92W). The majority of the gas wells have been drilled since 2001.

The majority of the gas wells are drilled from the northwest flank of the Divide Creek anticline, across Hunter Mesa, and onto Grass Mesa. A number of wells are also drilled on the northeast flank of the Divide Creek anticline, along Divide Creek, and extending east into the Gibson Gulch area.

Currently gas reservoirs including Mamm Creek, and Divide Creek are being developed within the study area from sandstones of the Upper Cretaceous Mesaverde Group. The gas with varying amount of condensate and formation water is primarily being produced from low permeability sandstones within the Cretaceous Williams Fork Formation of the Mesaverde Group. Gas is also being produced from deeper intervals including the Cameo Coal, Rollins, Cozzette and Corcoran. The fields are being developed using a strategy of the "multiple-well single location concept" where a number of wells are directional drilled from a single pad.

To enhance the permeability and stimulate production from the low permeability "tight" gas sands, the wells in the study area are being hydraulically fractured. Hydraulic fracturing is a process where large quantities (hundreds to thousands of gallons) of fluids (mostly potassium chloride) with sand are injected at high pressure into the producing interval in order to increase gas production by fracturing the sandstone. The sand is added to the fracture fluid to keep the fractures open after the pressure is released.

Since the drilling of the Starbuck #1 well a total of 978 wells have been drilled and an additional 234 wells have been permitted and 141 have abandoned status. The number of wells drilled in 2005 is biased low due to timing of this study. Based on the available data the permitted wells consist of the following:

- 904 producing wells (PR)
- 33 shut-in wells (SI)
- 9 wells waiting on completion (WO)
- 8 wells listed as temporarily abandoned (TA)
- 12 wells plugged and abandoned (PA)
- 9 wells dry and abandoned (DA)
- 2 injection wells (IJ)
- 1 domestic well (DM)
- 141 abandoned (permitted and undrilled) locations (AL) and
- 234 locations with permit requests or permitted and waiting to drill (XX)

Thirty-six different operators were responsible for drilling the 978 wells. Figure 4-1 shows the cumulative number of wells permitted and or drilled by eight of the most active operators in the study area. As seen in the figure, EnCana is the most active operator with 777 wells.

The majority of the drilling activity has occurred since 1999 when the number of wells drilled that year more than doubled from the previous year. From 1999 through 2004 the drilling activity has increased every year as shown in Figure 4-2. For the period between 1999 and August 2005, 880 wells have been drilled and completed. COGCC had not completed the record keeping and data entry for 2005 at the time the report was finalized.

Table 4-1 provides information on the well status and a break down of the drilling activity by year beginning in 1959 through August 2005.

Table 4-1
Well Status and Drilling Activity by Year

Year Drilled	Well Status								
	PR	SI	TA	WO	DA	PA	IJ	DM	Total Number of Wells Drilled by Year
1959						2			**2**
1961					1	1		1	**3**
1962					1				**1**
1965					1				**1**
1966					1	1			**2**
1974							1		**1**
1976						1			**1**
1982	4					1			**5**

Table 4-1
Well Status and Drilling Activity by Year

	Well Status								
1983					2				**2**
1988					1				**1**
1991	3				1				**4**
1992						1			**1**
1993	2								**2**
1994	18					1			**19**
1995	7		1						**8**
1996	25	1	1						**27**
1997	24								**24**
1998	13	2							**15**
1999	36		1						**37**
2000	66	1		1	1				**69**
2001	68	6	4						**78**
2002	92	7	1						**100**
2003	221	13		1		1			**236**
2004	243	3		7		3	1		**257**
2005*	82								**82**
Total by Well Status	**904**	**33**	**8**	**9**	**9**	**12**	**2**	**1**	**978**

Note: Represents the 2005 well count available from COGCC as of August 2005

As indicated in Table 4-2, the earliest gas wells that are currently still producing were drilled in 1982. The wells are located in Sections 20 and 22, T6S, R92W, and Sections 7 and 34, T6S, R93W. Gas is produced from the Mesaverde Formation. Table 4-2 summarizes the four producing wells.

Table 4-2
First Producing Wells in the Study Area

Well	Current Operator	Field	Location				Measured Total Depth	Producing Interval
			qtr	Section	Township	Range		
Mobil #11-20	Barrett Corp	Mamm Creek	NESW	20	6S	92W	8230	5514'–6948'
Friport #14-22	Barrett Corp	Mamm Creek	SESW	22	6S	92W	8270	5516'-6270'
Clough #9	Williams Prod	Rulison	SENE	7	6S	93W	9840	9461'-9816'
RH Ranch #1	EnCana	Mamm Creek	CSW	34	6S	93W	10050	6856'-9844'

Since the first producing wells were drilled in 1982 an additional 880 gas wells have been drilled. Locations of all of the wells are shown in Figure 4-3. A significant part of the strategy for developing the low permeability gas fields within the study area is to directionally drill the wells from pads using the "multiple-well single location concept". Bottom-hole locations of the directional wells were also plotted on Figure 4-3 for those wells where bottom-hole coordinates were available.

4.2.1 Well Depth Ranges

Measured total depths of the wells within the study area range from 820 feet to 18,422 feet below ground surface. The Benzel #36-12B (H35B) drilled by EnCana to a total depth of 820 feet is located in the SENW, Sec 35, T6S, R93W. The well was originally planned for a total depth of 7500 feet but was plugged and abandoned at 820 feet because there was access from another well location. The deepest well in the study area is the O'Connell #F11X-34P drilled by Mobil Oil Corporation in 1992. The well located in the NWNW Section 34, T7S, R92W reached a total depth of 18,422 into the Leadville Formation. By township the wells range in depth as follows:

- T6S, R92W –1,995 feet to 8,677 feet (average depth of 6,800 feet)
- T7S, R92W –3,690 feet to 18,422 feet (average depth of 8,300 feet)
- T6S, R93W - 820 feet to 10,210 feet (average depth of 6,400 feet)
- T7s, R93W – 6,253 feet to 11,200 feet (average depth of 8,300 feet)

4.2.2 Top of Gas

The top of produced gas for the Williams Fork Formation was determined from perforation intervals on 465 wells. The top of produced gas ranges from approximately 2,950 feet to 9,116 feet below ground surface with the shallowest production occurring in the southeast portion of the study area on the Divide Creek anticline.

The depth to the top of gas increases or becomes deeper from the Divide Creek anticline area to the north and west in the study area, towards deeper portions of the Piceance Basin. In July 2004, COGCC required that all new wells in the Mamm Creek field area be cemented to 500 feet above the top of gas.

4.2.3 Surface Casing Depths

Surface casing is installed at each gas well location for several purposes, including: isolation of the upper water bearing formation from hydrocarbon-bearing fluids, protect against blowouts or uncontrolled well flows during drilling, and is cemented from the total casing depth to the ground surface. Surface casing depths are currently required to "reach to a depth below all known or reasonably estimated utilizable domestic fresh water occurrence" (COGCC 2003). Additionally, in the Mamm Creek field, surface casing depths commonly exceed the maximum depth of usable groundwater to provide borehole integrity in the upper portion of directionally drilled wells.

Surface casing data was reviewed to determine the depths the surface casing was set within the Wasatch Formation. Surface casing data was available for 924 wells. Surface casing setting depths were reviewed and a histogram is shown in Figure 4-4. Setting depths ranged from 223 feet to 5,193 feet, and the majority of setting depths are between 700 and 1,200 ft bgs. The mean depth is 1013 ft bgs, and the median depth is 850 ft bgs.

The locations of all surface casings less than 600 feet deep are shown in Figure 4-6. Six hundred feet is the maximum depth of water wells within the study area. Approximately 97 wells had surface casing set at 600 feet or shallower. Surface casing ranged in size from 6.625 inches in diameter to 14.875 inches. The wells are located throughout the study area but the majority are concentrated in Sections 31, 32, and 33 of T6S R92W and Sections 3, 4, 5, 6, 7, and 18 T7S R92W as shown on Figure 4-6.

- Eleven wells within the study area had surface casing set from 223 feet to 400 feet. The Benzel 26-8D well and Benzel 26-9C well had surface casings set at 223 feet and 248 feet respectively. Those wells are located in the NESE Section 26 T6S R93W.
- The Scott No.1 located in the SESE Section 25 T6S R92W has surface casing set at a depth of 300 feet.
- Wells Federal RU14-6 and Federal RU 34-6 located in Section 6 T6S R93W have surface casing set at 316 feet and 317 feet respectively.
- Wells Youngberg 11-7, 13-7 and 22-7 located in Section 7 T6S R93W have surface casing set at depths of 329 feet, 320 feet and 322 feet respectively.
- The Rose Ranch 10-14 well located in NENW Section 15 T7S R93W had surface casing set at a depth of 354 feet.
- The Dunn 9-1C located in Section 7 T6S R92W had surface casing set at a depth of 400 feet and the Hill 16-3 located in the NWNE Section 16 T7S R92W had surface casing set at a depth of 400 feet.

4.2.4 Bradenhead Pressure

Bradenhead pressure is pressure in the annulus measured at the wellhead, and is indicative of gas under pressure within the well annulus. Although wells with measured bradenhead pressures may indicate micro-annular gas migration from completion problems (incomplete cementation of the well annulus), a slow leak in the production casing, or a wellhead seal leak, or the presence of thermogenic or biogenic methane present in shallower rock intervals (i.e. Wasatch Formation). Because the well annulus interval above the producing interval and below the surface casing is not sealed, if the cause of the elevated bradenhead pressure is not corrected through remedial cementing, gas and other formation fluids could move up the well annulus from the producing zone. There is a potential for fluids or gas to enter fractures (if present) below the base of the surface casing, within the overlying Mesaverde or Wasatch Formation and migrate outward from the borehole. These hydrocarbons could potentially reach a shallow groundwater aquifer or surface water body in the study area. The COGCC has encountered instances where bradenhead pressure originating in one well on a pad has charged one or more of the other wells present on that pad, indicating that gas can migrate within the shallow subsurface located above the gas producing zone.

As of July 23, 2004 COGCC instituted new requirements for measuring and reporting bradenhead pressure in the Mamm Creek Field area. COGCC requires measurement of bradenhead pressure at intervals of 6, 12, 24, and 72 hours after production casing has been cemented. Additionally COGCC requires immediate notification if any bradenhead pressures exceed 150 pounds per square inch gage (psig), the wellhead is “blown down” and monitoring of bradenhead pressure is conducted. If elevated pressures persist, a remediation procedure must be prepared for COGCC approval. However, remediation by perforating the production casing and squeezing cement behind the casing is only performed as a final measure. These regulations also require production casing to be cemented up to a height of 500 feet above the top of gas. URS did not analyze the data to determine how many existing gas wells in the study area meet the new regulations now in place for the Mamm Creek field.

Bradenhead pressure data for 2004 and 2005 were obtained from COGCC for 193 EnCana wells and other producer wells in 2004. The information provided for 2004 only included initial pressure data, and not monthly pressure readings. The EnCana data for 2005 had bradenhead pressure measurements from 148 wells ranging from 150 psi to 850 psi. An additional XX wells had measured bradenhead pressures between 100 and 150 psi. The bradenhead pressure data was used by COGCC to calculate a pressure gradient at the surface casing shoe to determine if the gradient exceeded a conservative rock fracture gradient of 0.50 psi/ft. The gradient exceeded the rock fracture gradient in three wells. In addition the hydrostatic gradient of 0.433 psi/ft was exceeded in an additional 12 wells. COGCC requires monthly monitoring of bradenhead pressure and the field engineer is informed by the operator when any well exceeds 150 psi. The cause of the bradenhead pressure is investigated by the operator and conditions are reported back to COGCC.

The bradenhead data has been compiled on Table 4-3. The wells with bradenhead pressures exceeding 100 psi have also been posted on Figure 4-5. Most of the wells with elevated bradenhead pressures are located on the north-northwest flank of the Divide Creek anticline and within the Hunter Mesa area. Many of the wells where elevated bradenhead pressures have been reported are located in areas where linear features are mapped.

Bradenhead pressures ranging from 100 psi to 400 psi were measured in 20 wells with surface casing set at depths of 600 feet or less. Nine of the wells with bradenhead pressures ranging from 110 psi to 400 psi are located in Sections 25, 32 and 33 T6S R92W, One well with a bradenhead pressure of 270 psi is located in Section 36 T6S R93W. Seven wells with bradenhead pressures ranging from 100 psi to 280 psi are located in Sections 4, 5, 7, 8, and 23 of T7S R92W. Three wells with bradenhead pressures ranging from 140 psi to 190 psi are located in Sections 10 and 11 T7S R93W.

The majority of the wells (approximately 175) with measured bradenhead pressures in 2004-2005 of 100 psi or greater were drilled in 2003 or earlier. Thirty of the wells were drilled between 1982 and 1999. Eight of the older wells with bradenhead pressure ranging from 100 psi to 500 psi are located in Sections22, 25, 26, 31, 32, and 33T6S R92W. Thirteen of the older wells with bradenhead pressures ranging from 100 psi to 500 psi are located in Sections 4, 5, 6, 7, 8, 17, and 18 T7S R92W. One of the older wells with a bradenhead pressure of 270 psi is located in Section 36 T6S R93W. Eight of the older wells with bradenhead pressures ranging from 100 psi to 240 psi are located in Sections 1, 10, 11, 12, and 13 T7S R93W.

4.3 DRILLING AND PRODUCTION PIT LOCATIONS

Drilling pits, also termed reserve or mud pits, have historically been utilized at each drill pad to temporarily contain drilling mud and production fluids during the drilling and completion of gas wells. These pits were typically unlined, and have the potential to allow infiltration of produced water, condensate, and dissolved methane into underlying groundwater. However, within the study area, drilling pits are typically lined with a synthetic material, which reduces the risk of releases from the pit.

The COGCC electronic database has records for 37 production pit locations within the study area. Production pit locations are shown in Figure 4-6. The majority of the 37 pit locations shown on Figure 4-6 are located in T7S R92W oriented in a north-south direction near Mamm Creek.

4.4 PLUGGED AND ABANDONED AND OLDER WELLS

Although downhole pressure and mud weight data is sparse in the COGCC database, the Williams Fork Formation is considered overpressured relative to typical hydrostatic pressure gradients (Kaiser and Scott 1996). Plugging and abandoning procedures for oil and gas wells have become more rigorous during the history of drilling within the study area, and the presence of older plugged and abandoned wells may pose a risk to overlying surface and groundwater resources. There are a total of 29 wells that have been abandoned (dry and abandoned, and plugged and abandoned), and 33 shut-in wells. Wells that are shut-in, require mechanical integrity tests and reporting to COGCC at 5 year intervals. These well locations are shown in Figure 4-6. The wells are located throughout the study area however several are clustered in T7S R92W in the Divide Creek Anticline area and along Mamm Creek. Several wells are located in T6S R92W near Dry Hollow Creek. A number of the wells are located in the Hunter Mesa and Grass Mesa areas and several wells are clustered in T6S R93W near Helmer Gulch.

The age of a gas well was also evaluated. Older gas wells are assumed by URS to have a higher risk of potential problems such as metal corrosion and seal deterioration than more recently completed wells. The COGCC database shows eighteen (18) gas wells were completed prior to 1984. There were no wells drilled from this time period to 1991. Figure 4-6 shows the locations of older (pre-1984) wells in the study area. These wells should be considered for additional evaluation.

4.5 WATER PRODUCTION RATES

The original statement of work for this project requested information regarding the volume, handling and disposal of produced water. The flow rate of produced water during the initial completion test is recorded for most gas wells in the COGCC database. It is unknown how the initial production rates compare to production rates over time for the individual wells. The Mamm Creek field is considered a dry gas field, meaning relatively little water is produced from an individual conventional gas well. However, all of the producing gas wells produce some small quantity of condensate or oil as well as water. There are a number of coalbed methane (CBM) wells within the eastern half of the study area that produce relatively larger quantities of water. CBM wells require pumping of water from the well to reduce formation pressure to promote desorption of the gas from the coal.

Typical water production rates, based upon initial gas well completion test results for 777 conventional wells in the COGCC database, range from 1 to 1,677 barrels of water per day. The average water production rate is 70 barrels per day (2,940 gal per day or about 2 gpm). For the 10 CBM wells identified by COGCC in the database, the average water production rate is 27 gpm.

Table 4-4
Average Water Production Rates

	Water (BBL/day)
Conventional Wells	
Number of Wells Tested	777
Minimum	0.33 BBL/d (<1 gpm)
Maximum	1677 BBL/d (49 gpm)
Average (median)	70 BBL/d (2 gpm)
CBM Wells	
Number of Wells Tested	10
Minimum	139 BBL/d (4 gpm)
Maximum	1673 BBL/d (47 gpm)
Average (median)	938 BBL/d (27 gpm)

Figure 4-8 is a graduated symbol map for initial water production from well tests entered into the COGCC database for approximately 777 conventional gas well locations. There are few significant water production trends on this figure. The water production rates for individual wells varied from low to high at many of the multiple well pad locations.

Produced water is stored in aboveground storage tanks (ASTs) located on each well pad. It is our understanding from talking with EnCana field engineers that the water is periodically removed from the tanks and transported by truck for treatment or disposal.

There are currently three centralized E and P (exploration and production) waste management facilities permitted within the study area. These facilities treat or handle produced water. They are the Hunter Mesa evaporation facility located in Sec 1 T7S R93W, the former Snyder Oil pond up on Dry Creek in Sec 26 T6S R93W, and the Lake Fox water storage facility on Grass Mesa in Sec 9 T7S R93W. Other wastes go to other E and P facilities located outside of the study area.

Two injection wells have been drilled for disposal of produced water and potentially brine. One is the Mamm Creek discovery well, the Jenks Schaeffer #1, located on Hunter Mesa in Sec 12 T7S 93W that was recompleted in the Corcoran and is planned to handle an injection rate of 4,000 BBL per day. The Benzel #2, located in Sec 26 T6S 93W, was recently drilled and completed within the Corcoran. This well initially produces gas, but will be permitted as a disposal well after the gas has been recovered.

4.6 SUMMARY

URS reviewed and evaluated much of the available data and identified factors that could either have a greater potential to allow upward migration of natural gas and fluids that could impact surface and groundwater resources. This included the depth of surface casing relative to the bottom depth of freshwater resources (the deepest water wells are 600 ft bgs in the study area), bradenhead pressure data, locations of plugged and abandoned wells, and the age of abandoned and existing wells.

5.1 HYDROCHEMISTRY OBJECTIVES

The primary objective of this section of the report is to review and interpret the groundwater and surface water quality for the study area, and seek geochemical evidence of potential impacts to water quality resulting from natural gas exploration and development and other anthropomorphic activities.

Specific objectives of this water quality section include:

- Compiling publicly-available surface water and groundwater quality data (chemical analyses of water samples) that are potentially useful to the investigation.
- Standardizing or "normalizing" the analytical data in preparation for its use in charting and data interpretations. Meeting this objective involved issues such as identifying primary and quality control samples, standardizing concentration units, analyte names, and distinguishing data for filtered versus unfiltered water samples.
- Reviewing water quality data for missing major constituents, and selecting the best quality analyses in terms of charge balance for interpretations of water-types and major ion chemistry. If sufficient data are available, comparison of calculated versus measured total dissolved solids (TDS) may also be performed to determine if important constituents have not been identified and analyzed.
- Reviewing the data and published literature to identify potential, geochemical indicators of water quality impacts due to gas exploration activities.
- Preparing maps, charts, and tables of analytical data and indicators, to aid the interpretation of geochemical water-types, the hydrochemical evolution of major ion chemistry, concentration trends, and local water quality anomalies. Major-ion-chemistry will be described using Piper plots and Stiff diagrams.
- The concentrations of potential contaminants of concern (COCs), selenium, fluoride, and nitrate/nitrite, will be mapped if sufficient data are available.
- Data for dissolved methane, and other organic compounds of interest in groundwater such as benzene, toluene, ethylbenzene, and xylenes (BTEX) will be evaluated. The presence of these organic analytes may be indicators of natural migration of hydrocarbons to shallow groundwater, and/or local anomalies may suggest potential impacts (leakage) from nearby gas well operations.
- Examining and interpreting stable isotope data for carbon and hydrogen in methane associated with groundwater samples.
- Interpreting and describing the general groundwater and surface water quality of the study area relative to local geology.
- Identifying areas potentially impacted from nearby gas exploration activities and geochemical anomalies, which may require further investigation and data collection during Phase II.
- Identifying significant data gaps and constraints limiting the present work that may be addressed and resolved by further investigation during Phase II.

The scope of work (SOW) is very detailed, and it requests several water quality data evaluation tasks be performed in addition to meeting the objectives listed above. For example, principal components analysis (PCA), and hierarchal clustering (cluster analysis) are requested for determination of distinct water-types, although the available data may not merit such sophisticated methods.

5.2 DATA AND EVALUATION METHODS

Analytical data for groundwater and surface water samples collected in the study area were evaluated as described below.

5.2.1 Data Sources, Data Quality, and Normalization

Data evaluated in this report were compiled from several governmental and private sources. These data were managed in a master Access database (Garfield_Maser.DBF). Data subsets were later retrieved from the database for specific purposes, examined, and standardized (or normalized) to facilitate data interpretations. There was a large amount of water quality data to be evaluated, and URS focused on utilizing as much of the data as possible for this study.

- Analytical results describing the study area groundwater and surface water samples were retrieved from databases managed by the COGCC, and from the United States Geological Survey (USGS).
- Consultants working for producers collected baseline water quality samples and the sample locations were surveyed using a GPS unit. Unfortunately, the GPS locations did not match coordinates the SEO has from well permits. Therefore, URS was unable to match many of the water quality samples from domestic wells to the well permits and driller logs. The result was that much of the water quality data could not be evaluated relative to the well depth or the lithologic unit the well was screened across.
- URS did not validate the data. Data validation is the principal means of evaluating the overall quality and usability of analytical data for environmental samples at many regulated sites (i.e. RCRA and CERCLA hazardous waste sites), but is not standard for many other types of analyses. Validation entails a rigorous review of the data package generated by an analytical laboratory for completeness and data usability, and follows published procedures such as Environmental Protection Agency (EPA) Contract Laboratory Procedures (CLP), or SW-846 guidelines for data evaluation.
- Data quality assessment (DQA) is a second level of quality assurance (QA) that does not qualify data records, but focuses on interpretation of field-collected quality control (QC) samples such as field-duplicates and equipment rinsates. DQA evaluates data against criteria for accuracy, precision, completeness, representativeness, and comparability. . DQA is not part of the present SOW, and such evaluations may or may not have been performed by the agencies providing the data.
- In general, the data quality objectives (DQOs), water sample collection procedures (standard operating procedures or SOPs), and analytical methods used to generate this data, are unknown. Also unknown is the level of quality assurance applied by the personnel who compiled and entered the data into the source databases.

- A number of data quality issues were observed in the data, which restrict its usefulness for this report. Important quality issues are listed below, along with the steps taken to minimize them during data normalization.
    - The stoichiometric units of some analytes are uncertain, or not reported (e.g., bicarbonate ion may be reported by the laboratory in mg/L as $CaCO_3$, or in mg/L as HCO_3). To maximize the amount of useful major ion data, it was necessary to assume that measured alkalinity (reported in mg/L as $CaCO_3$) is nearly 100 percent the result of bicarbonate ion, and then using alkalinity to calculate the bicarbonate concentration in mg/L as HCO_3. This is generally a safe assumption at the near-neutral pH values of most groundwater samples (Hem 1989).
    - Some analytical results are not reported (i.e., a null data field), or are reported as zero concentrations, presumably indicating a non-detect value. Where feasible, null or zero concentrations were replaced by the U-qualified reporting limit during data normalization.
    - Some of the reporting limits, or method detection limits are not available, and the analytical methods themselves are not identified.
    - There is uncertainty in distinguishing results for filtered water samples (i.e., dissolved concentrations) from unfiltered water samples (total or total recoverable concentrations). In some cases, the analyte name included the word “dissolved”. In other cases it was assumed the sample was unfiltered because of common industry practice for a given analyte. The majority of the water samples are likely unfiltered samples.
    - Because the data are a compilation from a number of sources, there is some variation in the names used for certain analytes. In many cases, URS standardized the synonyms and pooled the data under a single name.
    - When the data are compiled by sample-event (i.e., a single date of sampling at a single location), it is apparent that some water samples were analyzed for one or a few analytes (referred to here as “partial analyses”), while other samples have an extensive list of analytes (“complete analyses”). Partial analyses obviously have limited usefulness, specifically for use in evaluating a single constituent. Complete analyses are necessary for mapping major ion chemistry with Stiff plots and Piper diagrams (discussed later). Due to the large number of water samples collected, it was possible to compile a representative spatial distribution of major ion analyses for the study area.
    - Data for silica were essentially unavailable in the data, except for three analyses. The three silica concentrations ranged from 11.5 to 20.2 mg/L. Therefore, the present investigation calculated “total dissolved solids” (TDS) from the major ions used for Stiff plots (sulfate, bicarbonate, chloride, sodium, potassium, calcium, and magnesium) and ignored silica, minor, and trace constituents like Se, Ba, Sr, or fluoride. TDS was not calculated if any of the other major ions for Stiff plots was not analyzed or reported.
    - A large percentage of the water samples were obtained from domestic water wells and were therefore unfiltered to simulate the water consumed by residents. Because

unfiltered water samples contain various quantities of suspended solids (e.g., clay and silt particles), analyses of unfiltered samples should yield greater or equal concentrations of naturally occurring analytes, than analyses of filtered samples. Thus, TDS calculated for this report is likely biased high by the presence of particulates in the water samples.

- Initial calculations of charge balance error from the milliequivalents of major ions implied that many of the water analyses were inaccurate. However, much of the error was traced to uncertainty in the stoichiometric units of the bicarbonate ion. Some of the bicarbonate was reported as mg/L as HCO_3, while some was reported as mg/L as $CaCO_3$, and some of the data were in unknown units. The solution was to work around the problem by assuming that bicarbonate constitutes 100 percent of the measured alkalinity at the near-neutral pH values of most water. The calculated concentration of bicarbonate in mg/L as HCO_3 is then equal to 1.2192 times alkalinity reported in mg/L as $CaCO_3$ (Hem 1989).
- Visual examination of data tables showed a number of obvious outliers for TDS in which some values for the same well water were roughly 1000 times higher than other measurements for the well. This is probably the result of entering concentration data in both µg/L and mg/L units, but failing to consistently identify the correct units. A small number of obvious units inconsistencies or typographical errors were corrected. However, the overall water quality dataset for all analytes is of uncertain quality. Our professional judgment is that for the current investigation it is better to retain outlying observations that may indicate an actual geochemical anomaly or change in water quality, as opposed to discarding extreme values on the basis of a formal statistical outlier test. This is consistent with EPA's guidance which suggests retaining all outliers that can not be shown to be erroneous and corrected. It is also likely that the data for a given analyte are not normally distributed, but are drawn from multiple statistical populations (some of which may not be normal), because the samples were collected and analyzed by various methods from different groundwater source-rocks as well as ponds, streams, and springs.

5.3 DATA EVALUATION METHODS

This section expands on the data normalization discussed above by explaining the criteria used to select various subsets of the normalized data to produce geochemical maps and data interpretations. Statistical methods applied to the data are also described.

5.3.1 Geochemical Methods, Maps and Software

Water quality data used for describing major ion chemistry were averaged by analyte by location, when more than one data record was available, to reduce the effects of varied data collection methods and of potential outliers. Data selected in this investigation for describing major ion chemistry and water-types, were required to achieve an absolute charge balance error of less than or equal to 10 percent. Necessarily, none of the major ions were missing from the selected data. A total of 220 groundwater sampling locations met those criteria for major ion chemistry. Increasing the allowable charge balance error to 15 percent would not greatly increase the size of the dataset, but if a rigorous 5 percent error were adopted the dataset would be severely reduced by two-thirds.

The 220 groundwater and 61 surface water sampling locations selected for major ion chemistry were all assigned a lithology or rock unit which is believed to have produced the groundwater, or is spatially associated with the surface water. Driller's logs and well permits generally do not identify the lithology of the screened interval of a well, therefore it was necessary to infer the lithology. This was done by plotting the water sample locations on a geologic map, considering the dip and thickness of the rock units, and making assumptions regarding the depth and source of the water. The following unconsolidated and consolidated rock units were associated with water quality data:

- Alluvium associated with stream drainages and probably derived from the Wasatch Formation,
- Shire member of the Wasatch Formation (largely mudstone),
- Molina-like sandstone unit of the Wasatch (30-40% sandstone),
- Atwell Gulch member of the Wasatch (largely mudstone).

Surface water bodies were also classified as streams, ponds, or springs, for chemical discussions in this report. These classifications are based on codes provided in the database.

AquaChem version 5 software was used for identifying the water-types of surface water and groundwater samples. (Software brands and Company names are mentioned in this report for information only. URS does not endorse any particular company, or software brand). Through experimentation it was found that the simplest water-types (i.e., those with the fewest components, but at least one cation and one anion) were generated by setting AquaChem to define major ions as greater than 16 percent on a milliequivalent (meq) basis. As mentioned earlier, analytical results in the database are from unfiltered samples.

AquaChem was used to produce a variety of useful geochemical plots including: Piper plots, Schoeller plots, and Stiff plots. The shapes of Stiff plots vary with the major ion chemistry of a water sample and mapping Stiff plot symbols on a base map may show regional trends in water quality. Piper plots sometimes indicate relationships between water-types, such as ion exchange of Na for Ca and Mg. Schoeller plots are useful in identifying some geochemical indicators, as discussed later.

Graduated symbol maps (i.e. bubble plots) are widely used in this report to show the variation in analyte concentration across geographic areas. Each graduated symbol map is generated for a single chemical or ratio of constituents.

A number of geochemical indicators were computed and plotted in an attempt to relate major ion chemistry to the presence of organic compounds in the water. The rationale behind these indicators is discussed in the geochemistry background section.

Although not a parameter of geochemical interest, hardness is of concern for domestic water use. Hardness was calculated for the groundwater and surface water samples that met the 10 percent charge balance constraint. Calculated hardness in mg/L as $CaCO_3$ = 2.497 x Ca mg/L + 4.118 x Mg mg/L (Drever 1988). Water hardness in the study area is discussed later.

Sodium adsorption ratio (SAR) is a soil or water quality indicator for agricultural use. SAR measures the abundance of Na relative to Ca and Mg in irrigation water samples, or in soils. The current report computed SAR for the surface water and groundwater sample data used for other major ion interpretations. SAR is calculated by the following equation in which "_meq" indicates that the concentration units are milliequivalents per liter and "Sqrt" means square-root.

SAR = Na_meq / Sqrt((Ca_meq + Mg_meq) /2)   (Equation from Swift 2005).

Two issues biasing calculated TDS were discussed earlier: (1) the use of data for unfiltered water samples, and (2) the lack of silica data. It is important to note that for inclusion in the TDS calculation the bicarbonate concentration (in mg/L as HCO_3) was multiplied by 0.4917 as recommended by Hem (1989). This factor accounts for the loss of carbon dioxide and water expected during an equivalent analyzed TDS.

5.3.2 Statistical Methods and Software

This section discusses the statistical methods and software used for interpreting groundwater and surface water.

5.3.2.1 Principal Components Analysis

Principal components analysis (PCA) is a multivariate statistical method that attempts to boil-down the information contained in a large number of input variables, into a small number of new output variables called "principal components", or "SLCs". An SLC is a "standardized linear combination" of the original variables. PCA finds the set of SLCs, which taken together account for the variance of the original dataset.

The number of principal components output generally equals the number of input variables. However, standard practice is to select a subset of components, which account for most of the original variance. Different criteria have been proposed for deciding how many components to retain. One statistical software manual suggests retaining the minimum number of components that will account for at least 90 percent of the variance. However, each retained component should have practical meaning, or there is little point in keeping it.

Given statistical software, calculating components is straight-forward, but interpreting their meanings in chemical, hydrological, or physical terms is often difficult and controversial. Once a subset of the principal components has been retained "as interpretable", the original data can be interpreted in terms of the retained components. That is, the input data may be assigned "principal component scores", which may be used to rank or classify the input data.

Minitab 14 software was used for PCA of groundwater and surface water data (Minitab, 2005). The input variables were major ions in units of meq, and TDS in mg/L. Because of these different units the correlation matrix was used in PCA. The input surface water dataset contained the 61 locations used for major ion chemistry, while the groundwater dataset held data for 220 groundwater locations. The input variables were major ion concentrations in meq units. PCA results are interpreted in a later section of this report.

5.3.2.2 Cluster Analysis

Cluster analysis of variables attempts to classify chemical variables into homogeneous groups, when the groups are not initially known. This is sometimes done to reduce a large number of variables to a small number of composite variables that may be easier to interpret.

Minitab 14 software was used for hierarchical clustering of variables for two study area datasets (Minitab 2005). The surface water dataset contained the 61 locations used for major ion chemistry. The second dataset held the 220 groundwater locations used for major ion interpretations. The input variables were major ion concentrations in milliequivalent (meq) units, with the intention of interpreting the output clusters as water-types. The results are displayed in dendrograms and are interpreted in a later section of this report. URS selected the "correlation method" (not "absolute correlations"), and the "complete linkage" (furthest neighbor) method of linking clusters.

5.4 GEOCHEMISTRY BACKGROUND

Geochemistry background information is presented below to document the principles on which the water quality data of this report are being interpreted.

5.4.1 Natural Gas Chemistry

Natural gas is a mixture of light one to four carbon (C1 to C4) alkanes, higher molecular weight hydrocarbons (condensate), and inorganic gases (e.g. N_2, CO_2, H_2S, He) in various proportions. Hydrocarbon gases are produced by two different processes, biogenesis and thermogenesis. Anaerobic bacteria may decompose organic matter in sediments to form biogenic gas under near-surface, low temperature conditions. Biogenic gas is "dry" consisting mostly of methane, and it contains isotopically lighter carbon than thermogenic gas (GasChem 2005a). Biogenic gas is commercially produced in some areas of the country.

Thermogenic gas is formed at higher temperatures in sedimentary basins from thermal cracking of oil and/or solid organic matter in the sediments. Thermogenic gas can contain "wet gas" compounds like ethane, propane and butane, in addition to methane. Thermogenic gas may also have "condensate" consisting of compounds having 5 or more carbon atoms (C5).

Natural gas production in the Piceance Basin within Garfield County is from reservoirs of Eocene to Late Jurassic age (Johnson and Rice 1990). The gas produced in the Piceance basin is believed to be predominantly thermogenic gas. This gas becomes heavier isotopically ($\delta\ ^{13}C$ of -51.3 up to -29.1 per mil), and chemically drier (ratio of C1/(C1 to C5) of 0.26 to 1.00), with increasing thermal maturity of the reservoirs (Johnson and Rice, 1990). See the following discussion of stable isotope chemistry for an explanation of $\delta\ ^{13}C$ values.

5.4.2 Stable and Radioactive Isotope Geochemistry

Isotopes of elements including carbon, hydrogen, oxygen, and sulfur (respectively C, H, O, and S) are useful for identifying the origin of natural waters and fingerprinting sources of contamination in water samples. The present investigation is mainly concerned with stable (meaning non-radioactive) isotopes of C and H in methane because methane is the principal component of hydrocarbon gas.

The stable isotopes of carbon are ^{12}C and ^{13}C. Isotope fractionation processes, like photosynthesis, cause carbon stable isotope ratios to vary in different environments. Stable isotope data are usually reported as delta (δ) values in "per mil" units (parts per thousand, or $^{o}/_{oo}$). Delta for the ratio of $^{13}C/^{12}C$ in a sample is defined as follows, where $\delta(^{13}C/^{12}C)$ is referred to as $\delta\,^{13}C$.

$$\delta\,^{13}C \text{ per mil} = 1000 \text{ x } \{(^{13}C/^{12}C)\text{sample} - (^{13}C/^{12}C)\text{standard}\} / (^{13}C/^{12}C)\text{standard or,}$$

$$\delta \text{ per mil} = 1000 \text{ x } \{[(^{13}C/^{12}C)\text{sample} / (^{13}C/^{12}C)\text{standard}] - 1\} \qquad \text{(Stumm and Morgan 1981)}$$

A sample with $\delta\,^{13}C = -30$ per mil, for example, means that the sample is depleted in ^{13}C by 30 parts per thousand relative to the standard. The worldwide isotope standard for $\delta\,^{13}C$ is a Cretaceous belemnite from the Pee Dee Formation limestone of South Carolina.

Stable isotopes of hydrogen are ^{1}H and ^{2}H, and the latter is also known as deuterium or "D". The fractionation of interest is for D/H or δD, measured relative to a standard in a similar manner to the $\delta\,^{13}C$ equations previously discussed. The isotope standard for H (and for O isotopes) is "standard mean ocean water" or SMOW. By definition the δ D of standard seawater is 0 per mil, however, relatively large D/H fractionations are observed in other media because deuterium is twice as heavy as ^{1}H.

Biogenic and thermogenic gases can be differentiated using data for δD and $\delta\,^{13}C$, as well as chemical concentration data like the ratio of methane to the sum of heavier alkane gases (Jeffrey et al. 2005). Figure 5-1 does not use data from the study area, but shows how the concentration ratio of methane to ethane and propane can be used with $\delta\,^{13}C$ data to identify thermogenic gas (Jeffrey et al. 2005). Thermogenic gas tends to have more ethane and propane relative to methane, than does biogenic gas. Biogenic gas may also have more negative $\delta\,^{13}C$ values in the range -60 to –90.

Figure 5-2 does not use data from the study area, but illustrates how carbon and hydrogen isotopic data may be used to distinguish the mechanisms of methane formation (Jeffrey et al. 2005). The oxidation of methane to CO_2 in soils can shift the isotope ratios to less negative values, in the direction of the arrow on Figure 5-2 (Jeffrey et al. 2005).

Figure 5-3 shows the logic for using alkane ratios with δD and $\delta\,^{13}C$ stable isotopes, and with radioactive ^{14}C analysis to identify the source of hydrocarbon gases. In the figure, "pMC" is the percentage of modern carbon determined by ^{14}C analysis. Also note that Figure 5-3 uses the ratio of methane to total C1 to C5 alkanes.

5.4.3 Redox Geochemistry

Indicators of oxidation-reduction or "redox" environments are of interest in interpreting water quality which may have been impacted by natural gas. Organic compounds including natural gas, oil, and various grades of coal are excellent reductants (or reducing agents). Bacteria may also utilize some of these organic compounds as a carbon source for growth. If organic compounds are more abundant below the groundwater table than the concentrations of oxidants, then the geochemical environment of the groundwater will become reducing. How reducing it becomes depends on the net flux of oxidants and of reductants migrating into the groundwater and on bacterially-mediated redox reactions.

It has been established that in the presence of an excess of reductants, the strongest aqueous oxidants are destroyed first, followed by weaker oxidants in a sequence called the Gurney sequence (Gurney 1953). Ignoring trace elements in natural waters of pH near 7, the reduction sequence from first to last is: dissolved oxygen, nitrate, manganese (Mn IV), ferrous iron (Fe III), sulfate, and bicarbonate. In most surface waters and shallow groundwater, dissolved oxygen is the strongest oxidant (or oxidizing agent) present. The redox environment of water may be described by the measured concentrations of naturally occurring oxidants and reductants, or by the predominant redox processes (e.g., sulfate reduction, or methanogenesis) that are inferred to be taking place.

Redox environments may also be indicated by making “Eh measurements” of water samples. Although Eh measurements are easily made, the data are usually difficult to relate to specific redox reactions or equilibria in the water (Lindberg and Runnells 1984). Redox parameters and pH are unstable and may change during sample shipment and storage. Thus the best indicators of groundwater redox environments are field measurements (made at the time of water sampling) of dissolved oxygen (DO) and pH, followed by analysis of filtered and properly preserved water samples for laboratory analysis of dissolved: ferrous iron, total iron (divalent and trivalent Fe), manganese, sulfate and sulfide, nitrate and ammonia, bicarbonate and methane.

For example, if a shallow oxygen-bearing groundwater is suddenly contaminated with organic compounds, which bacteria can use as a substrate for growth, the environment becomes more reducing. The strongest oxidizing agents (oxygen and nitrate) are reduced first, and then sulfate concentrations are expected to decrease substantially due to sulfate reduction by sulfate-reducing bacteria.

5.4.4 Geochemical Indicators

Geochemical indicators are analytical parameters, or combinations of parameters (e.g., ratios), which indicate a geochemical environment, or condition of interest. This report is concerned with three sets of indicators: (1) indicators of water impact due to gas exploration activities; (2) indicators of geochemical or redox environments; and (3) indicators of general water quality for human consumption, domestic use, livestock, or agriculture. Redox indicators may be useful because the presence of hydrocarbon gases in groundwater is expected to produce a reducing environment.

Potential indicators of water impact from gas exploration activities and related redox indicators are discussed below:

- Analyses of the major and minor organic and inorganic constituents in natural gas may be compared between samples collected from potentially contaminated water and from a suspect gas well. Companies have used geochemical differences in natural gas constituent concentrations with a mixing model to allocate commingled gas production to discrete lithologic units (GasChem 2005b).
- Water and gases may be sampled and analyzed for their carbon stable isotope composition as a type of fingerprint. Carbon and hydrogen isotopes in methane can be used to distinguish biogenic gas from thermogenic gas, as the latter contains isotopically heavier carbon.

- Gas-rich basins like the Piceance Basin may have naturally occurring seepage or migration of methane and other light hydrocarbons upwards to shallow groundwater, or to the ground surface. The carbon and hydrogen isotopic composition of this naturally occurring background gas may differ from that of gas leaking from a nearby gas well because the gas well produces from discrete pay zones, which may have a unique isotopic signature.
- Detection in samples of well water or surface water of dissolved organic compounds like methane, ethane, propane, toluene, or benzene, which were analyzed for but not detected in the water prior to the installation of a "nearby" gas well. The definition of "nearby" depends on factors like the degree of natural fracturing and hydrologic properties of the formation rocks, but probably rarely exceeds 1,500 meters (m). The distance between the Schwartz 2-15B gas well and Divide Creek, for example, extends about 4,000 feet or about 1,200 meters.
- Another indicator would be the detection of components of drilling mud or hydraulic fracturing fluids in groundwater or surface water. If feasible, the same constituents should be analyzed for at the gas well to confirm that they were used during installation of the well. A wide variety of chemical products may be used in drilling and completing a gas well, including: drilling fluids (oil-based muds, synthetic-based muds, barite or similar weighting agents), acidizers, fracturing fluids, surfactants, foamers, defoamers (antifoamers), asphaltene dispersants, corrosion inhibitors, biocides and equipment degreasers. Material Safety Data Sheets (MSDSs) sometimes identify the chemicals used in these products, while others do not identify formulations that are considered trade secrets. COGCC states that the most commonly used drilling mud in the study area is bentonite-based. Bentonite is a naturally occurring clay mineral.
- Coalbed groundwater that contains methane is usually sodium bicarbonate (Na-HCO_3) or sodium bicarbonate-chloride (Na-HCO_3-Cl) water-types, that are depleted in sulfate ion, calcium ion (Ca), and magnesium ion (Mg) (Van Voast 2003). Conversely, some coalbed aquifers may contain groundwater that is rich in sulfate, Ca, and Mg, but <u>not</u> in association with dissolved methane (Van Voast 2003). This geochemical indicator is a "water-type" which occurs in part because sulfate reduction to sulfide takes place before methane production (methanogenesis) as an aqueous environment becomes increasingly reducing. Sulfate reduction in the presence of organic matter is also coupled to generation of bicarbonate (HCO_3^-) in water per the following equation (Chapelle 1993).

  $$2CH_2O + SO_4^{2-} \rightarrow H_2S + 2HCO_3^-$$

  Note that on a milliequivalent basis, one meq of sulfate is consumed for every meq of bicarbonate produced. Product H_2S usually does not accumulate to large concentrations because metal sulfides, like pyrite, precipitate. The Mg and Ca concentrations decrease through precipitation of carbonate minerals as the bicarbonate concentration increases, and ion exchange with sodium (Na). Schoeller plots are useful for recognizing this geochemical indicator, and are discussed later in this report.
- Based on the above Na-HCO_3 water-type indicator, mapping milliequivalent ratios like sulfate/bicarbonate may be a useful indicator of sulfate reduction.

- The presence of unexpected water-types with high TDS concentrations in shallow wells and/or surface waters may indicate migration or deeper formation waters to shallow depths, or to the surface. This migration could occur along naturally occurring fracture zones and/or be assisted by the presence of gas well boreholes. For example, many of the surface water and shallow groundwater samples from the study area are Ca and Mg bicarbonate water-types, while high total dissolved solids (TDS) Na-Cl and Na-SO_4 waters are more unusual. Sandstone gas reservoirs in the Williams Fork Formation and some of the Cameo coalbeds produce Na-Cl waters (Reinecke, Rice, and Johnson 1991).
- Changes in the concentrations of some dissolved redox-sensitive inorganic ions in water may indicate the onset of reducing conditions due to the presence of migrating natural gas, light hydrocarbons, or other naturally occurring organic carbon substrate. Sulfate reduction to sulfide is one example discussed above. However, there are other redox sensitive indicators. For example, groundwater in a shallow water well may contain measurable dissolved oxygen and or nitrate prior to the installation of a nearby gas well. If methane were to leak from the gas well into groundwater around the water well, the dissolved oxygen and nitrate may be reduced (both chemically and in concentration), while bicarbonate, dissolved iron, and dissolved manganese concentrations may increase. The aqueous iron (Fe) and manganese (Mn) would be primarily divalent species formed from the reduction of hematite, or ferric oxyhydroxides, and manganese oxide minerals.
- Several different ion ratios are mapped and interpreted in this report. The milliequivalent ratio of (Na+K)/(Ca+Mg) is used to indicate ion exchange and to distinguish waters evolving between Ca-rich water and Na-rich water. The mass ratio Cl/Br may also distinguish different water sources. For example, typical Cl/Br ratios are: precipitation 50 – 150, shallow groundwater 100 – 200, sewage water 300 – 600, and water from halite dissolution 1,000 – 10,000 (Davis, Whittemore, and Fabryka-Martin 1998).

Indicators of general water quality for human consumption and related household and agricultural uses are listed below.

- Comparison of analytical measurements of water samples against potentially applicable water quality standards. Useful standards may include:
    - EPA drinking water maximum contaminant levels (MCLs), and secondary standards (EPA 2005).
    - Colorado Water Quality Control Commission (CWQCC) standards for groundwater and surface water (CWQCC 2004, 2005). These include general standards, standards for specific drainage basins, and sometimes, site-specific, or industry-specific standards. Different sets of standards exist for drinking water, agricultural use, and for aquatic life.
    - COGCC rules and water quality monitoring requirements for conducting natural gas exploration in Colorado. The COGCC implements water quality standards established by the CWQCC.
- Hardness is an indicator of water quality for household use. Hard water can cause scaling in hot water heaters, and it prevents soap from lathering well. Water hardness is the concentration of dissolved metals in the water that can react with sodium-soaps to precipitate an insoluble residue (Drever 1988). Hard water is mainly due to elevated

concentrations of Ca and Mg, although minor and trace level constituents can contribute to hardness, including: Fe, Mn, Sr, Ba, Zn, and Al (NDWC 2005). Total hardness is usually defined (as in this report) in terms of Ca and Mg in units of milligrams per liter (mg/L) as $CaCO_3$. The degree of water hardness may be classified as in Table 2-2.

- Sodium adsorption ratio (SAR) is a soil or water quality indicator for agricultural use. SAR values may be used together with conductivity or specific conductance to classify the quality of irrigation water (KGS 2005). SAR measures the abundance of Na relative to Ca and Mg in irrigation water samples, or in soils. Soils with excess Na relative to Ca and Mg, are not very permeable for infiltration of rain or irrigation water, and elevated Na concentrations can be toxic to plants (Swift 2005). These sodic soils are often sticky when wet and become crusty, hard, and cloddy when dry (Swift 2005). The calculation of SAR was described earlier in the methods section.

5.5 GROUNDWATER QUALITY INTERPRETATIONS

The following text sections discuss the geochemistry and quality of groundwater in the study area. Initially the data are viewed for the entire study area for regional trends, then the data are classified and examined by the geology of the water source.

Figure 5-4 is a well location map which shows groundwater sampling locations selected for discussions of major ion chemistry. Wells are shown by well type (e.g., irrigation versus monitoring), and selected gas wells are also labeled for reference. Figure 3-1 is a reference map for the groundwater quality discussions.

5.5.1 Site-Wide Variations in Groundwater Quality

Groundwater quality generalizations are made below by evaluating the analytical data on a site-wide basis. This is done in the following subsections by using a variety of approaches: identification of water-types, scatterplots, graduated symbol maps of analyte concentrations and ion ratios, stable isotope chemistry, cluster analysis, principal components analysis, descriptive statistics, and data comparisons with water quality standards.

5.5.2 Water Types and Major Ion Chemistry of Groundwater

Groundwater analytical data with a charge balance error of less than 10 percent resulted in selection of 220 sampling locations for investigation of major ion chemistry. Out of the 220 wells, 195 locations represent domestic water wells or water supply wells, 21 locations are monitoring wells (all located near West Divide Creek), and 4 are irrigation wells. The inferred geologic source of the groundwater for these groundwater sampling locations is as follows: Atwell Gulch member 67 locations, Shire member 62, Molina-like member 72, and alluvial locations 19.

Water-types should be identified based on dissolved concentrations (i.e., filtered water samples), but very little dissolved data were available. Therefore, unfiltered concentrations were used for the following discussions of major ion chemistry. The use of unfiltered water samples introduces uncertainty into the water-type determinations due to the presence of unknown, but variable, concentrations of suspended solids in the water samples.

At the 220 locations, the most frequent water types are: Na-HCO_3 (49 locations), followed by Na-SO_4 (22), Na-SO_4-HCO_3 (16), Na-Cl (15), with various Ca and/or Mg-HCO_3 waters accounting for 41 more locations. Sodium is the dominant cation in groundwater at more than 60 percent of the sites. Ignoring mixed-anion water types, bicarbonate is the predominant anion at more than 60 percent of the locations.

Figure 5-5 ranks the groundwater types by the mean concentration of calculated TDS. The six highest TDS water types on the left-hand side of the figure are all Na-SO_4 waters or Na-Cl waters. It is speculated that the high-TDS water may be derived from deep groundwater of higher salinity, perhaps diluted by mixing with shallow groundwater. The deep groundwater may migrate towards the surface by following faults and fractures along structures like the Divide Creek anticline. All of the low TDS water-types (right-hand side of the figure) are metal bicarbonate waters. It appears that most shallow groundwater in the study area starts out as metal bicarbonate waters (Ca-HCO_3 or Mg-HCO_3 water), which evolve and pick up Na ion through ion exchange processes. As the Na increases, the residence time of the water is increasing, and its TDS is increasing. Some of the Ca, Mg, and bicarbonate may also be lost through precipitation of Mg-bearing calcite.

Figure 5-6 shows symbol colors coded to the water-type of the groundwater. Secondly, Figure 5-6 shows symbol areas scaled to the TDS of the water. Thirdly, the symbol shape is keyed to the inferred geology of the screened interval. For example, yellow circles on Grass Mesa indicate groundwater sampled from the Shire member of the Wasatch Formation with a Mg-Na-HCO_3 water-type and TDS below 1,000 mg/L. Study area generalizations include the following,

- Numerous water-types (see Figure 5-6 legend) are found across the region.
- TDS varies from less than 1,000 mg/L to nearly 6,000 mg/L.
- Low TDS water is generally located on Grass Mesa and along stream drainages, with the exception of Dry Hollow Creek.
- Dry Hollow Creek in Sec 34 T6S R92W and surrounding sections generally have elevated TDS waters, although TDS varies widely in this area, suggesting at least two different groundwater sources.

Earlier it was mentioned that plots of various ion ratios might indicate distinctive water sources, such as coal-bed methane waters and similar gas-bearing groundwater. One of the ratios of interest for identifying methane-bearing waters is the meq ratio of sulfate over bicarbonate (i.e., SO_4/HCO_3 ratio). Figure 5-7 is a scatterplot of the SO_4/HCO_3 ratios in groundwater plotted against chloride concentrations in meq/L. This figure seems to distinguish groundwater from the Shire (S in the legend) from Molina-like groundwater (M-l in the legend) at SO_4/HCO_3 ratios >2 and Cl concentrations >20 meq/L. Below these numeric thresholds the plot fails to discriminate the data.

Shire groundwater tends to have low SO_4/HCO_3 ratios (typically <2), which suggests an origin from infiltration of precipitation. Groundwater from the Molina-like sandstone interval exhibits a wider range of SO_4/HCO_3 ratios ranging from near-zero to 12. This may indicate the presence of more than one water type in this area.

Linear regression was performed of calculated TDS against measured TDS (Figure 5-8) for the 220 water samples that met the 10 percent charge balance criteria. These two parameters should closely agree if all major constituents of the water were analyzed, and were analyzed accurately. Figure 5-8 indicates excellent agreement between calculated and measured TDS, which implies that the plotted dataset is of good quality. The fitted regression line is TDS calculated = 1.09 x TDS measured –106.5 mg/L.

5.5.3 Cluster Analysis and PCA of Groundwater Major Ions

Cluster analysis of variables was performed on the data selected for describing the major ion chemistry of unfiltered groundwater. The variables in this clustering are the major ions: Ca, Mg, Na, K, sulfate, chloride, and bicarbonate. Mean meq concentrations of these ions at 220 groundwater sampling locations were used in the analysis. The intention was to see if cluster analysis of major ion variables would identify the same water-types that were identified by AquaChem based on analyzed abundance in meq units.

Figure 5-9 is a dendrogram showing the hierarchy of similarities between major ion concentrations measured in groundwater samples. Figure 5-9 implies that the following water-types should be important in groundwater: Na-Cl, K-HCO3, Ca-Mg-SO4, and some mixed Ca-Mg-SO4-HCO3 waters. Potassium is usually the least abundant of these major ions in pristine groundwater and surface water. Consequently the identification of a K-HCO3 water type would be geochemical anomaly, and AquaChem did not identify such a water-type in the study area. However, this cluster analysis does agree with AquaChem on the existence of the other water types, Na-Cl, Ca-Mg-SO_4, and Ca-Mg-SO_4-HCO_3 waters.

Principal components analysis (PCA) was performed on 8 input variables (components) representing the major ion composition of groundwater. Because the major ion data had meq/L units, and the TDS data were in mg/L units, a correlation matrix was used for PCA. Figure 5-10 is a scree plot of the PCA output, and Table 5-3 shows additional PCA output parameters. The principal components each accounting for more than 10 percent of the variance, are Ca (38 percent of the variance), Mg (26 percent), Na (13 percent), and K (11 percent). According to PCA, the chloride and bicarbonate concentrations contribute insignificantly to the variance and are considered unimportant components. However, this is at odds with the geochemistry, because it was shown earlier that bicarbonate water-types are very important in groundwater, and Na-Cl waters have also been identified in the study area.

5.5.4 Analyte Concentrations in Groundwater

A large number of graduated symbol maps of chemical concentrations and ion ratios in groundwater have been prepared for visual evaluation. All sampling locations with relevant data are plotted to show where data were collected.

The field-measured pH of groundwater has been mapped on Figure 5-11. Groundwater pH data for unpolluted waters are commonly in the range from about 6 to about 9 standard units (S.U.). Colorado basic groundwater standards for domestic water supply require pH to be in the range 6.5 to 8.5 S.U. Figure 5-11 suggests that most of the groundwater pH data fall in this acceptable range. Some of the lowest pH values are for monitoring wells located near the Divide Creek anticline area. Monitoring wells with low pH in this area include: 704163 (pH 6.13), and 704162 (pH 6.5). The domestic well with the lowest pH value was station 704221 (pH 5.43). However, COGCC checked on this result, and this value was reportedly measured with an older pH meter, but the meter was calibrated at the time. Subsequent pH measurements from this well have been

8.42 and 7.21 S.U. The pH of this sample was also measured in the laboratory, and a value of 8.71 S.U. was reported. Field and laboratory measurements of pH are typically variable, and therefore it has been URS experience that individual pH measurements are not a primary geochemical indicator, except for relatively high or low values (i.e. <5.5 or >8.5).

Previously, a low ratio of sulfate over bicarbonate was proposed as a possible indicator of a sulfate-reducing environment with accompanying bicarbonate generation. Such an environment might be associated with coal-bed methane waters, with the presence of thermogenic alkanes or biogenic methane in groundwater. Figure 5-12 is a graduated symbol map of the SO_4/HCO_3 ratio in groundwater. The mean (average) ratio value is 0.97, and 58 samples exceeded the mean. Eleven wells exceeded a ratio of 4.0. Low ratios are common on the map, possibly indicating either infiltration of precipitation high in bicarbonate or sulfate-reducing conditions across wide regions of the map. In fact, 95 wells out of 220 selected for major ion chemistry, had ratios <0.20. Based on the low TDS and methane concentrations for water quality data from the Grass Mesa area, the low SO_4/HCO_3 ratios primarily result from infiltration of precipitation.

There are 21 monitoring wells in the West Divide Creek drainage and near the Schwartz 2-15B gas well. Inspection of the data used to create Figure 5-12 indicates that 18 of the 21 wells have very low ratios below 0.20 SO_4/HCO_3, possibly indicating sulfate reduction. The low ratios are anticipated in wells completed within the alluvial aquifer, because bicarbonate is the dominant anion in the shallow water (discussed in a later section). Low SO_4/HCO_3 ratios in deeper bedrock well completions are more likely due to reducing conditions that may be caused by the presence of hydrocarbons in the area.

Surprisingly, there is a small cluster of wells in the Divide Creek anticline area, predominately west of Dry Hollow Gulch (T6S, R92W, near Sec 33 and 34) that have high SO_4/HCO_3 ratios up to about 12. This area of Figure 5-12 indicates a locally different water-type and water source in the Molina-like sandstone interval and some Atwell Gulch groundwater. The high-ratio locations are domestic wells including: 704035 (ratio 12.1), 703952 (ratio 9.9), 704502 (ratio 9.77), and 703260 (ratio 9.34). Other well locations with higher ratios are stations 704404 (2.4) and 704403 (1.8) located on the east side of Grass Mesa, and 704487 (2.4) located on Hunter Mesa near West Mamm Creek.

Groundwater sulfate concentrations are shown in Figure 5-13. Elevated sulfate concentrations are found in the same local area described above as having high SO_4/HCO_3 ratios. The highest sulfate concentrations are at domestic wells: 703986 (3,110 mg/L), 703992 (2,785 mg/L), 703952 (2,775 mg/L), and 704035 (2,100 mg/L). The last two wells were also mentioned as having high SO_4/HCO_3 ratios. The EPA secondary drinking water standard for sulfate is 250 mg/L (“salty taste” above this level). The mean value for the 220 major ion analyses is 329 mg/L, and 69 samples (about one-third) exceeded this standard.

Measured TDS is mapped on Figure 5-14. Measured TDS data were available for 1845 samples, more than the 220 samples with complete major ion results. The mean (average) measured TDS value is 1,000 mg/L, and values of 8,500 mg/L and 10,000 mg/L were measured. Approximately one-third of the samples exceed the average TDS value. Wells located near Section 34 of T6S R92W and Dry Hollow Gulch have relatively high TDS values. Water wells in this area also have higher specific capacities, which were inferred (Section 3) to result from the presence of fractures. These fractures may allow deeper groundwater with higher TDS values to mix with shallower groundwater in this area. One very high TDS value stands out on the map because it is located in an unexpected place, south of Rifle and apparently near the south edge of the Colorado River floodplain. It is domestic well 704479 with groundwater TDS of 8,800 mg/L.

Graduated symbol maps of chloride/bromide (Cl/Br) concentration ratios were prepared for unfiltered groundwater from 105 sampling locations. Maps based on meq ratios showed the same features as maps based on mass ratios. The mass ratio map, Figure 5-15, is discussed here and the observed ratios are compared to values in published literature. Figure 5-15 shows a range of Cl/Br ratios between approximately 50 and 570. The mean value is 143. The map indicates that the majority of the data available are from the eastern portion of the study area and that most of the ratios are below 310. Most of the Cl/Br mass ratios are less than 200 and greater than 50, which is indicative of shallow groundwater (100 to 200), and precipitation (50 to 150) (Davis, Whittemore, and Fabryka-Martin 1998). Deep formation waters, if associated with halite dissolution, are expected to have much larger ratios (1,000 to 10,000), than are seen in the data of this report. However, no data on the measured Cl/Br ratios of groundwater associated with natural gas production zones were available for this study.

The highest Cl/Br ratio on the map has a value of 569 at station 704152, a domestic well. This location has mean chloride and bromide concentrations of 773 mg/L and 3.8 mg/L, respectively. The cause of the anomaly is unknown, although septic water can have ratios of 300 to 600 (Davis, Whittemore, and Fabryka-Martin 1998). It is not simply the result of elevated chloride ion, because other stations on Figure 5-15 have higher chloride concentrations. Dissolved methane has been detected in this well on several occasions, and the fluoride concentration is also elevated above the National Primary Drinking Water Standard (EPA MCL) of 4.0 mg/L.

The meq ratio of nitrite over nitrate ion concentrations was mapped for groundwater from 29 locations at which both ions were detected (Figure 5-16). This ratio may be used as a redox indicator. Nitrite ion is an intermediate in the reduction of nitrate to nitrogen gas or to ammonia. Thus, high ratios of nitrite/nitrate indicate that nitrate reduction is probably occurring, but because measurable nitrite and nitrate remain, the environment is not yet sufficiently reducing for the onset of sulfate reduction. Figure 5-16 shows that most of the wells have very low nitrite/nitrate ratios indicating the rarity of nitrite relative to nitrate ion in most groundwater. However, areas of elevated nitrite/nitrate ratios show up at the wells listed below.

- Station 704221 a domestic well has a nitrite/nitrate meq ratio of 5.91
- Station 704195 a domestic well has a nitrite/nitrate meq ratio of 4.60
- Station 704500 a domestic well has a nitrite/nitrate meq ratio of 1.28
- Monitoring well 704181 has a ratio of 1.14.

All other wells with detectable nitrite and nitrate in their water have ratios below one.

Figure 5-17 is a graduated symbol map of the concentrations of nitrate ion, in mg/L as N, in unfiltered groundwater. Nitrate concentrations range from near zero to 163 mg/L, and the mean concentration from over 900 samples is 6.3 mg/L. The EPA drinking water MCL for nitrate is 10 mg/L. The potential detrimental health affects include death and are primarily for infants below the age of six months. The highest nitrate concentrations are found in water from irrigation wells 703930 (Sec and 703942, which have maximum values of 163 mg/L and 131 mg/L, respectively. These elevated concentrations may be due to fertilizer applications on nearby fields. The adjacent domestic water wells also have elevated nitrate concentrations. The largest nitrate concentration measured in a domestic well is 105 mg/L in well 703962. Approximately 15 percent of the domestic well nitrate water samples exceed the 10 mg/L MCL value. Roughly one-half of the domestic wells on Grass Mesa have exceeded the MCL for nitrate. Several wells along Dry Creek, East Divide Creek, and near Dry Hollow Gulch also exceed the nitrate MCL.

Figure 5-18 is a graduated symbol map of the concentrations of nitrite ion (in mg/L as N) in unfiltered groundwater. Nitrite concentrations ranged from non-detect to 3.23 mg/L, and the mean concentration for nitrite detections is 0.63 mg/L. The EPA drinking water MCL for nitrite is 1 mg/L and the potential detrimental health affects include death and are primarily for infants below the age of six months. Nitrite ion is less commonly detected than nitrate in most groundwater. Six domestic wells exceed the MCL for nitrite. These domestic wells are: station 704474 (3.2 mg/L), 704203 (3.06 mg/L), 704221 (2.96 mg/L), 704195 (1.95 mg/L), 704050 (1.2 mg/L), and 704899 (1.17 mg/L).

Fluoride concentrations in unfiltered groundwater are shown in Figure 5-19, a graduated symbol map. The EPA drinking water MCL for fluoride is 4 mg/L. Concentrations range from non-detect to 11.5 mg/L. The mean concentration detected for fluoride in 866 samples was 1.96 mg/L. Thirty-one wells (domestic, irrigation, and monitoring wells) were equal to or exceeded the MCL concentration in at least one sample. Fluoride groundwater concentrations exceeding the MCL are all located in the southeast quadrant of the study area, on or near the Divide Creek anticline. This suggests that the fluoride may have originated in deep formation groundwater (i.e. Mesaverde or deeper Wasatch Formations). The fluoride in groundwater in this area could also result from the presence of apatite, or another mineral containing fluoride, within the bedrock. The fluoride MCL is not exceeded in any of the water samples from the western half of the study area. The largest detected fluoride concentrations are between 10 and 11.5 mg/L in groundwater from domestic well 704012. Groundwater in monitoring well 704162 has 10.5 mg/L, and domestic well 703983 has 8.7 mg/L fluoride.

Selenium concentrations in unfiltered groundwater have been used to create the graduated symbol map, Figure 5-20. The EPA MCL for selenium is 0.05 mg/L. The range of selenium concentrations in groundwater ranged from non-detect to 1.0 mg/L. The mean concentration detected is 0.042 mg/L. However, samples from approximately 42 wells exceeded the MCL. Similar to the fluoride concentration distribution, all of the MCL exceedances for selenium are from water wells located in the east half of the study area, with the exception of one well along Dry Creek and one well near west Mamm Creek. The highest domestic well selenium concentration is station 703960. Selenium has been analyzed from one sample from this location, and had a concentration of 1 mg/L. This well should be resampled and tested for selenium again.

Figure 5-21 is a graduated symbol map using pie charts to display the relative percentages of the seven major cations and anions. The size of each pie chart is scaled to the relative calculated TDS concentration. Several observations are made from this figure. There are many water well locations with a low TDS sodium-bicarbonate water type, particularly on Grass Mesa, upper Hunter Mesa, and the southeast portion of the study area. Wells with higher TDS concentrations and a sodium-sulfate signature dominate the Dry Hollow Gulch area, and are also present in the upper Hunter Mesa area. Water well locations with higher TDS concentrations typically have a sodium-chloride water type. Areas with this water type are located east and west of Grass Mesa, along west Mamm Creek, the upper Dry Hollow Gulch area and the area about one mile west of Dry Hollow Gulch (west of the West Divide Creek seep area), and the southeast corner of the study area.

Figure 5-22 is a plot of select cation and anion concentrations versus water well depth. For the major cations and anions, concentrations generally decrease with water well depth for calcium, magnesium, and bicarbonate. Concentrations of sodium, sulfate, chloride, and TDS generally increase with water well depth. The trend lines for each ion may be skewed by the inclusion of data for wells with the higher TDS sodium-chloride and sodium-sulfate water types. If these data were removed from the graph, the trend lines may differ.

Benzene concentrations were evaluated within the study area as a potential indicator of hydrocarbon releases. All of the benzene concentrations detected within the study area are located in the immediate vicinity of the gas seep on West Divide Creek (Sec 12 T7S R92W). Benzene in this area exceeds the EPA drinking water MCL of 5 µg/L in groundwater. The highest benzene concentrations (reported here as means) are at stations: 704133 (330 µg/L), 704132 (314 µg/L), and 704134 (244 µg/L). These means are based on analyses of water samples collected prior to mid-August, 2005.

5.5.4.1 Dissolved Methane in Groundwater

Methane has been detected in many water wells in the study area. Methane occurring within groundwater beneath the study area has been shown to originate from biogenic and thermogenic sources. As discussed earlier in this section, stable isotope and gas compositional data are required to interpret the origins of dissolved methane. Methane concentrations in domestic groundwater wells are mapped in Figure 5-23, and include biogenic, thermogenic, and unknown types of methane. The data for the map were cutoff to only show values below 38 mg/L. Methane values above approximately 38 mg/L are suspect, as this is the saturation concentration of methane in water for the general elevation of the study area. The presence of thermogenic methane in shallow water wells could be due to natural conditions (migration of gas from underlying Mesaverde Group reservoirs and/or the Wasatch Formation along naturally occurring fracture zones), from oil and gas drilling, completion, or production activities. The origin of biogenic methane can occur by microbial fermentation of organic matter or metabolization of dissolved bicarbonate, or from biogenic sources at or near the homeowner residence.

Dissolved methane occurrences detected in groundwater are almost entirely restricted to the east side of the study area. This distribution pattern was also observed for the fluoride and selenium data. There are approximately 40 well locations with methane concentrations exceeding 1 mg/L, which is near the lower limit for methane that can be analyzed for stable isotope and gas compositional constituents. A methane concentration of 2 mg/L or higher may be more appropriate for collecting free gas for stable isotope and gas composition analysis. This information is necessary to evaluate if the methane has a biogenic or thermogenic origin. However as a conservative practice, wells with methane concentrations of 1 mg/L or higher may warrant additional sampling. Analyses of water samples from 8 of these locations had been completed but not reported with the water quality database received by URS from COGCC, and five of these samples were determined to be of biogenic origin, and three samples were found to be of thermogenic origin. The origin of the methane in 29 of these samples is unknown at this time, but additional groundwater sampling and analysis appears appropriate for these locations. This data is shown in Table 5-4.

To better evaluate if water in the study area has been impacted due to gas well activities, it would be necessary to have water quality data obtained from many water wells before the current drilling activities began, to establish baseline conditions. Additionally, to determine the origin of the methane in the groundwater (biogenic versus thermogenic), the composition of gases present and isotopic data are necessary. Because water quality data prior to 1997 was not available for this study, establishing the origin of the methane in the groundwater may be difficult for portions of the study area, including the southeast corner of the study area.

URS completed a review of methane sample results and gas well drilling by year. A summary of this analysis is presented in the following section. The COGCC database contains 1,968 sample results collected over an almost nine-year period. Based on the analytical data provided to URS 1997 was the first year with methane analytical results. There were no sample results for 1998 or 2000 in the database. The samples were collected from 395 distinct sample locations including surface water and groundwater sources. The water was analyzed for a number of different constituents including methane. Only the methane results are discussed in this section.

The surface water sources include creeks, rivers, ponds, seeps, and springs within the study area. Groundwater sources include domestic wells, irrigation wells, water wells, air sparging wells and monitoring wells. The water-sampling program has varied every year in terms of the sample locations, the number of samples collected, and the parties collecting the samples. Samples can be collected prior to drilling in new areas to serve as “baseline” samples. As the drilling activity has increased, the number of water samples collected has increased concurrently.

The methane data has been organized by sample year to evaluate and understand the potential impacts to water sources associated with the oil and gas drilling activities completed during that year or previous years. Based on a review of the data, water samples were first collected and analyzed for methane in 1997. The following sections discuss the methane results starting with 1997. For each of the following figures (maps), the water wells and gas wells present prior to the year in question are shown in black, and the water and gas wells completed within the year in question are shown in red.

5.5.5 1997 Methane Results and Oil and Gas Drilling Activity

Water was sampled and analyzed from five water wells in 1997. The wells are located in the eastern and southeastern portions of the study area along the Divide Creek anticline as shown in Figure 5-24. The methane sample results are provided on Table 5-5. Two of the wells had low concentrations of methane above reporting limits at approximately 6 and 9 micrograms per liter (µg/L). Methane was detected at 6 µg/L in well 703806 from a sample depth of 100 feet. The well is located in the NENW Section 34 T6S R92W. Methane was detected at 9 µg/L in well 703016 from a sample depth of 500 feet. This water well is located in the SENW Section 35 T7S R92W.

Oil and gas drilling activity for the time period was reviewed to evaluate the potential impacts to the water sources. A total of 104 wells were drilled during or prior to 1997 and those are plotted in Figure 5-24. The majority of the wells are located north and west of the sampled water wells. The closest gas wells are at least 5,000 feet from any of the domestic wells sampled in 1997. Of interest however are two nearby former gas wells that were drilled in 1959, and after failed attempts to produce commercial quantities of gas the wells were plugged and abandoned.

The Starbuck #1 well located in the NWNW of Section 25, T7S, R92W was drilled to a total depth of 5,710 feet. The Starbuck #1 well is the oldest well in the study area (completed in

1959), and fresh water was recovered during drill stem tests (DSTs). Initial shut-in pressures recorded during the DSTs indicate that the area in the southeast portion of the study area is over pressured by approximately 200 psi/ft at a depth of 3,700 feet.

After the production casing was set at 5,710 feet the pressure built up to 300 psi and water and gas flowed up the annular space outside of the production string to the surface. An attempt to control the gas and water flow was made by pumping 800 barrels of 12.5 pound per gallon mud without success. The gas and water flow was finally controlled after several attempts and a total of 635 sacks of cement were pumped down the well.

After the production casing was set several zones were perforated between the intervals at 3,000 feet to 5,650 feet. Commercial gas production could not be established and the well was plugged and abandoned in 1967.

The Philpott JO #1 well located in the NWNW Section 36 T7S R92W was drilled to a total depth of 5,425 feet. During drilling DSTs were conducted across several zones. Initial shut-in pressures of 1,760 psi recorded during the DST indicate an area of overpressure at a depth of 2,800 feet.

Surface casing was set at 257 feet and the production string was set at 5,050 feet. The well was perforated and tested however perforation records are incomplete. Several zones were perforated within the interval from 3,581 feet to 3,944 feet. An interval between 3,944 feet to 3,978 tested gas at a rate of 734 MCF/D and water at a rate of 8.4 barrels per hour. In May of 1964, the well was shut-in after testing the perforated zones. It was plugged and abandoned in 1966. Based on the plugging information the annulus was still under some pressure after the well was plugged. The driller's notes indicate that the annulus was making a cup of water every hour with a slight amount of gas.

In 1993 the landowner notified the COGCC that the abandoned well was leaking oil and water to the surface and threatening water quality in his irrigation ditch. COGCC responded and oversaw the subsequent plugging and abandonment of this location during 1994. Ten barrels of liquid oil were removed from the location and approximately 7 cubic yards of oil soaked soil was disposed of at a waste disposal facility.

The Philpott JO #1 well is approximately 3,500 feet from the Starbuck water well. After slowly leaking hydrocarbons for nearly 30 years the well could possibly be a persistent source for the methane contamination in the groundwater.

5.5.6 1999 Methane Results and Oil and Gas Drilling Activity

Four domestic water wells were sampled in 1999. The well locations are shown in Figure 5-25. Methane was detected at water well station 703086 at 0.450 mg/L at a sample depth of 100 feet (an increase from 0.006 mg/L in 1997). The well is located in the NENW Section 34 T6S R92W. Methane was not detected above reporting limits in the other three wells. The sample locations are shown in Figure 5-25. The sample results are provided on Table 5-6.

The oil and gas drilling activities for 1998 and 1999 were reviewed to evaluate the potential impacts to the water sources. Fifty-two wells were drilled during 1998 and 1999. The wells consist of 49 producing wells, 2 shut-in wells and 1 temporarily abandoned well. The well locations are shown in the Figure 5-25. The majority of the new gas wells are located in the central portion of the study area near the northwest flank of the Divide Creek anticline and on

Hunter Mesa. No new gas wells were drilled close to domestic well station 703086 that might explain the increased methane detections. A review of the closest wells to the 703086 water well did not reveal any obvious completion or production difficulties. Methane clearly exists in groundwater near the area of the 703086 well but the source of the methane is unknown and could be naturally occurring. However, five of the gas wells completed in 1997 (Figure 5-24) are located hydraulically upgradient (southwest) of water well 703086, and may have contributed to the increase in methane in this well.

5.5.7 2001 Methane Results and Oil and Gas Drilling Activity

Thirty groundwater samples were collected from 25 water wells during 2001. The sample locations are shown in Figure 5-26, as are the previously existing and newly installed water wells. The sample result summary for methane is provided in Table 5-7. The wells are located respectively in Sections 22, 23, 27, and 28 of T6SR93W, Sections 3 and 9 of T7S R93W, Sections 29 and 33 of T6S R92 W, and Sections 4 and 7 of T7S R92W. Methane was detected in 10 of the water samples. The concentrations ranged from 0.0014 mg/L to 12 mg/L. Nine of the 10 wells with methane detections are located in adjoining sections (Dry Hollow and Mamm Creek area) where a number of gas wells were located and also completed that year. Six of the methane detections were from two water wells that are approximately 1,100 feet apart in Section 33 T6S R92W. Well station 703230 was sampled four times over a short period with methane detections ranging from 0.0017 mg/L to 12 mg/L. Well station 704012 was sampled twice with detections of methane respectively at 0.050 mg/L and 0.210 mg/L. Well station 703961 located approximately 100 feet north of well 704012 in Section 33 T6S R92W was sampled once, and methane was detected at a concentration of 0.001 mg/L. Well stations 704073 and 704011 located along Mamm Creek approximately 7,500 feet to the northwest of well station 704012 had methane concentrations of 2.3 mg/L and 0.160 mg/L respectively.

Twelve well locations were sampled on Grass Mesa. Only one well had a detection of methane. This well is located in Section 28 T6S R93W and had a methane detection of 0.0014 mg/L. A second well located to the north approximately 1,000 feet was sampled however methane was not detected above reporting limits in that well.

A total of 78 gas wells were drilled in 2001 within the study area. The wells consisted of 68 producers, 4 wells that were temporarily abandoned and 6 shut-in gas wells. The well locations are shown in Figure 5-26. Although several gas wells were already present in the area hydraulically upgradient of water well stations 703230, 704012, and 703961, several new gas wells installed from the G33 pad in 2001 are in very close proximity to these water wells. The close proximity of the gas wells to the water wells, may indicate that the wells have been impacted from methane due to drilling, however these water wells are located in an area of pronounced linear features. Three linear trends intersect near this area; a west-northwest to east-southeast feature, a northeast to southwest feature, and a curvilinear feature that trends north-south in this area. The occurrence of methane in groundwater in this area may be caused by natural migration up along fracture zones associated with subsurface movement along these deeper structural features.

Several new gas wells were drilled within a few thousand feet of well stations 704073 and 704011 as shown in Figure 5-26. However, there were a number of gas wells already present southwest of this area. These water well locations are located hydraulically downgradient from multiple gas wells drilled on Hunter Mesa.

One new gas well was present in 2001 near well station 704061. The gas well is located southeast, and uphill from the water well. It is unknown if the low concentration of methane that was detected in this water well is related to the drilling activity in the study area.

5.5.8 2002 Methane Results and Oil and Gas Drilling Activity

Eighty-four water samples were collected for methane analysis from 82 locations during 2002. This was over three times the number of samples collected in 2001. Sixty-five groundwater samples were collected and 19 surface water samples were collected. The surface water samples included 10 river samples and 9 spring samples. The sample locations are shown in Figure 5-27. The sample results are provided on Table 5-8.

Of the 84 samples collected methane was detected in 29 samples. Methane was detected in: 24 groundwater samples with concentrations ranging from 0.0022 mg/L to 15 mg/L; 3 river samples ranging from 0.001 mg/L to 0.054 mg/L; and in 2 spring samples at 0.0011 mg/L and 0.0017 mg/L.

The groundwater samples were collected from wells located throughout the study area as shown in Figure 5-27. The groundwater samples with methane detections are located in the following sections: 3, 7, 8, 15, 23, 24, 26, 27, and 34 of T7S R92W; Sections 20, 29, 33, and 35 of T6S R92W, and Sections 19, 24, and 35 of T6S R93W.

The spring samples with methane detections are located along the east slope of Grass Mesa in Section 11 T7S R93W and above Middle Mamm Creek in Section 30 T7S R92W. The river samples with methane detections are located in Sections 14 and 26 T7S R92W and Section 22 T7S R93W. A surface water sample was collected from Dry Creek at a location in the SENE of Section 22 T7S R93W. Methane was detected in the sample at a concentration of 0.054 mg/L.

A total of 100 gas wells were drilled within the study area during 2002. Ninety-two gas wells were completed, 1 well was drilled and temporarily abandoned and 7 gas wells were shut-in. The well locations are shown in Figure 5-27. There were no new wells completed in the southeastern portion of the study area (Upper Divide Creek) where a number of groundwater wells, springs and West Divide Creek were sampled. However, many new gas wells were completed in this area during 2002. As seen on Figure 5-27 many of the groundwater wells sampled during 2002 had concentrations of methane above the reporting limit.

A number of the sampled groundwater wells in this portion of the study area are located hydraulically downgradient of the Starbuck and Philpott plugged and abandoned wells located respectively in Sections 25 and 36 T7S R92W. Both of the wells encountered flowing conditions that at the time were difficult to control. The Philpott well was found to have been leaking hydrocarbons up the surface in 1993, almost 30 years after the well was plugged. It seems likely in the absence of other data that methane and possibly other formation fluids leaking from the Philpott well migrated into and contaminated the Wasatch aquifer. It’s likely that over the 30 years of leaking the contamination probably migrated a significant distance which could be acting as continual source of methane for a number of water wells in the area. It is also possible that one or more of the other dry holes in the vicinity if the Philpott well may have or is contributing to the inferred methane plume.

Two wells in Section 8 T6S R92W and one well located in the NWNE Section 8 T7S R92W were sampled for methane in 2002. Methane was detected in all of the wells at concentrations ranging from 0.002 mg/L to 15 mg/L. Well 703258 located along Mamm Creek in the SENW Section 8 T6S R92W had a concentration of methane at 15 mg/L. Well 703262, located in the SWSE of Section 8 T7S R92W and approximately 3,500 feet south of well 703258, detected methane at 0.002 mg/L. Well 704037 located approximately 3,200 feet west of well 703258 had a methane concentration of 5 ug/l. These wells are within an area of high-density directional drilled gas wells, many of which were drilled years prior to the first methane samples collected. A bottom-hole location from one of the directionally drilled wells appears to be almost underneath the 703258 water well.

Well 704012 was sampled again in 2002. Methane was detected at a concentration of 1.9 mg/L. The well located in SWNE of Section 33 T6S R92W is approximately 500 feet north of the G33 pad. Based on the sampling results from 2001 and 2002 the groundwater in the vicinity of the water well has been impacted from methane. The methane may originate naturally from movement up fracture zones, or from drilling activities conducted in this area.

Methane was detected in two wells along lower Mamm Creek in Section 29 T6S R92W of the study area. Well 703261 located in SWNE of Section 29 T6S R92W had a methane concentration of 350 µg/L. Well 704068 located in SESW of Section 29 T6S R92W had a methane concentration of 0.140 mg/L. Both of these wells are located near the intersection of regional linear subsurface features. Until about 2000 to 2001, there were no gas wells within almost two miles hydraulically upgradient of these water wells. However, the water wells are located downgradient from the Hunter Mesa drilling region.

Well 704009 located in the northwest corner of the study area in NESW Section 19 T6S R93W had a methane detection of 6.9 mg/L. Based on the data provided to URS there are not any gas wells in the vicinity of this well. Resampling of this well should be considered.

Well 704433, located in the NWSW Section 35 T6S R93W, was sampled twice in 2002. Methane was detected at 0.0058 mg/L in March and at 0.0018 mg/L in July. The well is on the west side of Hunter Mesa in an area that has been heavily developed by gas drilling. Few water wells exist in the area and it is not possible to fully determine if the gas development has impacted the water quality. Low methane concentrations could be caused by biogenic sources.

5.5.9 2003 Methane Results and Oil and Gas Drilling Activity

One hundred twenty-three water samples were collected for methane analysis from 109 sample locations in the study area during 2003. The sample results are provided on Table 5-9. A total of 105 groundwater samples were collected, and 18 surface water samples were collected including 4 river samples, 2 pond samples, and 11 spring samples (Figure 5-28). The majority of the sample locations were in the eastern portion of the study area in Townships 6 and 7 South and Range 92 West in or around the Divide Creek anticline and clustered around Dry Hollow Creek in Sections 33 and 34 of Township 6 South and Range 97 West where previous sampling has indicated high levels of methane are present in groundwater. Samples were also collected from groundwater wells on Grass Mesa and Hunter Mesa.

Methane was detected in 59 of the 123 samples collected. Fifty-two of the methane detections were in groundwater samples with concentrations ranging from 0.008 mg/L to 585 mg/L.

However, methane concentrations exceeding approximately 38 mg/L are suspect, as this is the saturation value for methane dissolved in water at the study area elevation. The remaining 7 detections were in surface water samples where methane was detected in 1 river sample at 0.0095 mg/L, 4 spring samples with concentrations ranging from 0.0011 mg/L to 0.210 mg/L, and 2 pond samples at 0.035 mg/L and 0.049 mg/L.

Most of the samples with detected methane had relatively low concentrations below 2 mg/L. Several areas however, had elevated levels of methane in groundwater. The area around Dry Hollow Creek in Sections 29, 33, and 34 within Township 6 South and Range 92 West had methane concentrations of 2.9, 7.07, and 11 mg/L respectively, and resampling of these well locations is suggested.

Elevated concentrations of methane (above 2 mg/L) in groundwater were detected in the southeast portion of the study area (central portion of the Divide Creek anticline) in Sections 10, 15, 23, 26, 27, and 28 within Township 7 South and Range 92 West. This portion of the study area prior to 2003 experienced little gas development activity. The elevated concentrations ranged from 1.5 to 36.7 mg/L of methane. These wells should be considered for resampling and isotope and gas compositional analysis. The wells with elevated methane concentrations include:

- Well 703942 in the NWSE Section 10 at 1.6 mg/L (February 2003)
- Well 703545 in the NWSW Section 15 at 1.75 mg/L (January 2003)
- Well 703996 in the NENW Section 26 T7S R92W at 7.7 mg/L (January 2003)
- Well 704074 in the NENE Section 27 T7S R92W at 12.5 mg/L (January 2003)
- Well 704334 in the NWNE Section 28 T7S R92W at 36.7 mg/L (January 2003)

Methane concentrations in groundwater for the Grass Mesa and Hunter Mesa areas were mostly below reporting limits and listed as not-detected, however very low concentrations of methane were detected in three samples at concentrations ranging from 0.008 to 0.0024 mg/L. The samples were located in Section 28 Township 6S Range 93W (well 704062), Section 4 Township 7S Range 93W and Section 7 Township 6S Range 92W.

The spring sample locations were scattered across and around the perimeter of Divide Creek anticline. Spring samples with methane detections are located in Section 11 T7S R93W and Section 30 T7S R92W. The river samples with methane detections are located in Sections 14 and 26 T7S R92W and Section 22 T7S R93W. Both of the pond samples had methane above reporting limits at 0.035 and 0.049 mg/L.

A total of 152 gas wells were drilled within the study area during 2003. The wells consisted of 146 producing wells and 6 shut-in gas wells. The well locations are shown in Figure 5-28. The majority of the new wells were drilled in the central portion of the study area on Hunter Mesa and Grass Mesa. Several wells were drilled in the southeastern portion of the study area on the Divide Creek anticline.

Methane was detected at elevated concentrations (greater than 2 mg/L) in groundwater in Sec 23 T7S 92W. Several new gas wells had been completed in the area, although the methane could be due to natural causes or lingering contamination from the old plugged and abandoned wells in the area. The Questar Fairview #1 was drilled during 1976 in the SWSW Sec 23 T7S 92W.

Circulation was lost during drilling, at a depth of 6,325 ft bgs, and the well was not completed. The EnCana, Fazzi 26-4D1 (D26) gas well located in the NWNW Section 23 T7S R92W is the closest newly completed gas well to the water wells that had concentrations of methane in this area. The Fazzi 26-4D1 (D26) was spudded in August 2002 and completed in April 2003. The well was drilled to a total measured depth of 3,818 feet and surface casing was set at 550 feet. URS did not receive any information regarding drilling or completion problems with this well. Therefore it is not possible to draw a conclusion as to the potential impact of drilling and completing this well may have had on nearby groundwater quality.

5.5.10 2004 Methane Results and Oil and Gas Drilling Activity

There were a total of 838 samples collected and analyzed for methane in 2004. The samples were collected from 180 sample locations. Groundwater accounted for 470 samples from 126 locations including 91 domestic wells, 3 irrigation wells, 26 monitoring wells and 5 air sparging wells. There were 368 surface water samples collected from 54 sample locations. The surface water sample locations included 14 river locations, 1 creek location, 25 spring locations and 14 pond locations.

The sampling in general was clustered around several areas including the Grass Mesa area in T6S R93W, the Hunter Mesa area in T7S R93W, the previous methane impacted area near Sections 27, 33 and 34 T6S R92W, the southeast corner of the study area, and the gas seep in the West Divide Creek area (Sections 1, 2, 11, and 12 in T7S R92W. The majority of the sampling was in the West Divide Creek seep area, an area of ongoing investigations that will not be discussed here although the methane results of the groundwater and surface water are presented in Table 4-9 for informational purposes.

There were 26 groundwater samples and 4 surface water samples collected from the Grass Mesa area. The sample locations are shown in Figure 5-29. The sample results are provided on Table 5-10. Methane was detected in 3 of the groundwater samples at very low concentrations ranging from 0.0012 mg/L to 0.0082 mg/L. Methane was not detected in the surface water samples above reporting limits.

Seven groundwater samples and 2 spring samples were collected in Sections 2, 11, and 14 T7S R93W near Hunter Mesa. Methane was detected in domestic well 704372 at a very low concentration of 0.00086 mg/L. Methane was detected in one of the spring samples located in Section 11 at a concentration of 0.001 mg/L.

A total of 21 groundwater samples from 12 domestic wells and 12 surface water samples were collected from 12 locations around Dry Hollow Gulch in Sections 27, 33 and 34 T6S R92W, the previously identified area with elevated methane concentrations. Methane was detected in 17 groundwater samples ranging in concentrations ranging from 0.0032 mg/L to 14 mg/L. The methane could be of biogenic or thermogenic or mixed origin. However, the sample locations where methane exceeds 1 or 2 mg/L should be resampled and analyzed for stable isotope and gas composition to better evaluate the origin of the methane. Methane was not detected above reporting limits in any of the surface water samples.

Two domestic wells and 6 springs were sampled along Mamm Creek in Section 29 T6S R92W. Methane was detected in the groundwater samples at concentrations of 2.7 mg/L from domestic well 704068 and 6 mg/L from domestic well 704073. Methane was not detected in the surface water samples.

Five domestic wells and 4 surface water locations consisting of 2 springs and 2 ponds were sampled in the southeast corner of the study area. The domestic wells are located in Sections 15, 23, and 25 of Section 7S R92W. The ponds are located in Section 9 and the springs are located in Sections 15 and 25. Seven samples were collected from the 5 domestic wells. Methane was detected in 5 of the samples and concentrations ranged from 0.0008 to 28 mg/L in domestic well 703943 located in the NWNE of Section 23. Five samples were collected from the four surface water locations. Methane was detected in 4 of the samples with the concentrations ranging from 0.017 mg/L to 0.4439 mg/L.

A total of 256 gas wells were drilled in 2004 within the study area. The wells consisted of 249 producers, 2 wells that were plugged and abandoned, 4 wells waiting on completion and 11 shut-in gas wells. The wells were installed in every township in the study area. The well locations are shown in Figure 5-27.

A large concentration of wells was drilled in Section 32 T6S R92W within a quarter mile of Mamm Creek. This area is approximately one mile west from the area with higher methane concentrations first identified from the 2001 sample data.

Most of the wells installed in Section 32 had bradenhead pressures above 150 psi. The Couey 32-15 well had an initial bradenhead pressure of 400 psi and a gradient at the surface casing shoe of 0.795 psi/foot, which is greater than the natural hydrostatic pressure gradient of 0.433 psi/foot. The bradenhead pressure data for the wells drilled in Section 32 is included in Table 4-3. The Couey 32-15 well is located in the NWSE Section 32 and approximately 900 feet northeast of domestic well 703250. Well 703250 was sampled in 2004 for methane. Methane was not detected above reporting limits in the groundwater sampled from well 703250.

Domestic well 704068 is located in the SESW of Section 29, approximately 4,500 feet from the Couey 32-15 well and less than ½ mile from other gas development in Section 32. Groundwater sampled in 2004 from well 704068 had a methane concentration of 2.7 mg/L.

Domestic well 704073 is located in the NESW of Section 29 and approximately 1,450 feet northwest of well 704068. Methane was detected in well704073 at 6 mg/L.

Both wells 704073 and 704068 have had methane detections during several past sampling events. However the methane concentrations increased in 2004, which might indicate a methane release from the gas development in Section 32.

5.5.11 2005 Methane Results and Oil and Gas Drilling Activity

There were 872 samples collected and analyzed for methane through August 2005. The samples were collected from the 184 sample locations shown in Figure 5-30 and summarized in Table 5-11. A total of 515 groundwater samples were collected from 144 locations including 97 domestic wells, 3 irrigation wells, 27 monitoring wells and 15 air sparging wells. There were 357 surface water samples collected from 40 sample locations. The surface water sample locations included 12 river locations, 16 spring locations, 1 seep location, and 11 pond locations.

The sampling in general was clustered around several areas including the Grass Mesa area in T6S R93W, the Hunter Mesa area in T7S R93W, Mamm Creek drainage in sections 17, 20, and

29, T6S R92W, Sections 22, 23, 25, and 26 T6S R92W, Sections 31 and 36, T6S R92W, the previous area of high methane concentrations near Sections 27, 33 and 34 T6S R92W, the South Divide Creek area, and the gas seep in the West Divide Creek area Sections 1, 2, 3, 10, 11, and 12 in T7S R92W. The majority of the sampling was in the West Divide Creek area, an area of ongoing investigations and won't be discussed here although the methane results of the groundwater and surface water are presented in Table 5-10 for informational purposes.

There were 7 groundwater samples and 1 surface water sample collected from the Grass Mesa area. The sample locations are shown in Figure 5-30. Methane was not detected in any of the groundwater or surface water samples above reporting limits.

Six groundwater samples were collected in Sections 1, 2, 13, and 24 T7S R93W near Hunter Mesa. Methane was detected in domestic well 704487 at a concentration of 16 μg/L.

A total of 39 groundwater samples from 22 domestic wells and 9 surface water samples were collected from 6 ponds and 3 springs in Sections 27, 33 and 34 T6S R92W, a previously discussed methane impacted area. Methane was detected in 24 groundwater samples ranging in concentrations ranging from 0.0021 mg/L to 10 mg/L. The location of the 10 mg/L methane concentration was well 704392, located in the SESW of Section 27. COGCC has reviewed stable isotope and gas composition analyses for this well and has determined that the gas in this well is biogenic in origin. Methane was detected in 2 of the pond samples at concentrations of 0.015 mg/L and 0.053 mg/L. The samples were collected from the ponds located in the NESE of Section 34 and the SWSE of Section 27 respectively.

Four domestic wells and 5 springs were sampled at Mamm Creek in Section 29 T6S R92W. Methane was detected in 3 of the groundwater samples at concentrations of 0.2209 mg/L, 1.4 mg/L and 0.230 mg/L. Methane was not detected in the surface water samples. One well and 1 spring were sampled at Mamm Creek in Section 32 T6S R92W. Methane was not detected above reporting limits in either sample. One spring sample was collected in Section 5 T7S R92W at Mamm Creek. Methane was not collected above the reporting limit in the sample.

A total of 13 samples were collected from 12 domestic wells located in the northeast portion of the study area in Sections 22, 23, 24, 25, and 26 T6S R92W. Methane was not detected above reporting limits in any of the groundwater samples. A total of 4 surface samples were collected from the NWNW Section 25. Two samples each were collected from 1 pond location and 1 river location. Methane was not detected above reporting limits in any of the samples.

An area on the east edge of the study area in Section 25 and 36 T6S R92 W was sampled. Five groundwater samples were collected from 3 domestic wells. Methane was not detected in any of the samples above the reporting limit.

Seven wells were samples in the southeast corner of the study area. The wells are located in Sections 23, 24, 26, 27, and 35 T7S R92W. Methane was detected in 6 of the 7 wells at concentrations ranging from 0.026 mg/L to 8.9 mg/L. A river water sample was collected from Section 35. Methane was not detected above the reporting limit in the river sample.

A total of 151 gas wells have been drilled to date in 2005 (COGCC database from September 2005). The wells consisted of 148 producers, and 3 wells waiting on completion. The wells were installed in every township in the study area but are loosely clustered around the intersection of the four townships similar to 2004 drilling activities. The well locations are shown in Figure 5-30.

The drilling activities for 2005 are very similar to 2004. The same general areas continued to be developed. Most of the drilling for 2005 was at Grass Mesa and Hunter Mesa. Groundwater and surface sampling for methane in those areas did not reveal any areas of significant impact. Methane was not detected above reporting limits for most of the samples collected in the Grass Mesa and Hunter Mesa area. When methane was detected it was present at a low concentration. However, there are few water wells located on the central portion of Hunter Mesa, and therefore few groundwater sample locations.

The area along Mamm Creek experienced a dozen or more new gas wells as development pushed toward the north. Methane sampling along Mamm Creek indicates that a plume of methane is present in the groundwater in the vicinity of Mamm Creek and has impacted water wells. Several wells in Section 32 T6S R92W had high bradenhead pressures in 2004. Nine wells in Section 32 had bradenhead pressures at or above 150 psi during 2005, which could increase the potential for methane releases from the producing formation to the groundwater aquifer.

5.5.12 Stable Isotope Chemistry of Groundwater

The concepts behind the use of stable isotope chemistry were discussed earlier. Figure 5-31 plots carbon and hydrogen stable isotope measurements of methane sampled from groundwater. The legend shows the water samples from domestic wells (DOM) and from monitoring wells (MW). By referring to Figure 5-2 and Table 5-1, the isotope ratios plotted on Figure 5-31 may be classified as indicating thermogenic methane or microbial (biogenic) methane. The curved bands on Figure 5-31 denote these classifications.

Most of the domestic wells appear to contain biogenic methane based on the stable isotope ratios of Figure 5-31. However, three domestic wells (stations 703928, 703938, and 703943) have ratios which plot in the middle of Figure 5-31. These three wells have methane of uncertain origin, which may be gas from multiple sources, although the low percentages of ethane and other heavier hydrocarbons may suggest gas of biogenic origin. Most of the monitoring wells are located in the West Divide Creek seep area, and they appear to have thermogenic methane associated with the gas release from the Schwartz 2-15B gas well.

5.5.13 Descriptive Statistics and Comparisons Against Water Quality Standards

The water samples used in this analysis were collected from water wells and were unfiltered to represent water that could be used for consumption. Many analytes measured in unfiltered groundwater were compared against water quality standards intended for filtered water data (i.e., dissolved concentrations). Table 5-12 contains descriptive statistics by well group (e.g., domestic wells), then by analyte. For example, the table row that begins "Irrigation Well Fluoride", summarizes fluoride analyses for groundwater samples from irrigation wells. About 90.7 percent of the analyses detected fluoride in an irrigation well and the mean fluoride concentration was 2.1 mg/L. About 21 percent of the fluoride analyses of irrigation water exceeded the MCL of 4 mg/L and the Colorado basic groundwater standard, while 51 percent of the analyses exceeded the Colorado basic standards for surface water (2 mg/L). Despite the irrigation well example, all data in Table 5-12 were compared against drinking water standards, not agricultural standards.

The percentage of wells with constituents that exceed Colorado basic ground water standards is summarized in Table 5-13.

5.5.14 Hardness and SAR of Groundwater

Water hardness is of concern if the water is to be used for household uses. Water hardness causes scaling problems in hot water heaters and excessive consumption of soaps. Figure 5-32 plots calculated TDS versus the hardness calculated from groundwater Ca and Mg concentrations. The data are nonlinearly related, although lower hardness tends to be found in low TDS waters. Figure 5-32 shows that about half of the hardness measurements are greater than 300 mg/L as $CaCO_3$, which indicates very hard water (Table 5-2). Quantile plots of calculated hardness by lithology indicate approximate median hardness values in mg/L: alluvium 360, Shire 300, Molina-like 350, Atwell Gulch 250.

SAR and conductivity data are useful for classifying the general quality of water which may be used for irrigation. The U.S. Department of Agriculture uses SAR along with conductivity data by to classify irrigation waters in terms of "sodium hazard" and "salinity hazard" (Figure 5-33). SAR values were calculated for groundwater at 126 locations which also had conductivity measurements. The wells were grouped by type with the results shown in Table 5-14.

Although only three irrigation wells were considered in Table 5-14, their mean SAR of 19.4 and mean conductivity of 2,065 micromhos per centimeter (umho/cm), plots in the "C3-S3" hazard class on Figure 5-33. The C3 code indicates high salinity water that may be unusable for irrigation of soils that have restricted drainage (KGS 2005). The S3 code indicates a high sodium water which may require special soil management (e.g., good drainage and leaching), because of potentially harmful levels of exchangeable sodium.

5.5.15 Quality of Groundwater from the Shire Member

Figure 5-34 is a map of Stiff plots for groundwater sampled from rocks of the Shire member of the Wasatch Formation. Red dots show the well locations that provided data for constructing the map. Most of the wells in the Grass Mesa area have low-TDS groundwater that is rich in bicarbonate. The low-TDS suggests that the Grass Mesa groundwater originated from local infiltration of rainwater and snow-melt. By contrast, high-TDS Na-Cl water-types are seen to occur both east and west of Grass Mesa, but not on the mesa. The high-TDS water probably has a deeper source (i.e. lower Wasatch or Mesaverde) because TDS, sodium, and chloride concentrations often increase with the age or residence time and depth of the groundwater. The most frequent water types in Shire rocks are: $Na-HCO_3$ (9 sampling locations), $Ca-Mg-HCO_3$ (8), $Mg-HCO_3$ (8), $Mg-Ca-HCO_3$ (7), and $Mg-Na-HCO_3$ (5). Miscellaneous water-types were found at 25 additional Shire locations.

Schoeller plots were mentioned during the earlier discussion of chemical indicators of coal-bed methane waters. Figure 5-35 is a Schoeller plot of $Na-HCO_3$ groundwater's sampled from domestic and water supply wells in the Shire member. Note that the vertical axis is on a log scale and major ions are listed across the bottom of the plot. The analysis lowest in SO_4 and Mg is from station 704009 and looks similar to water signatures from coal-bed methane production water in the southeast Piceance Basin by Van Voast (2003). That is, it has high Na, HCO_3, and chloride, in combination with low sulfate and low Ca and Mg.

5.5.16 Quality of Groundwater from the Molina-like Sandstone Unit

Figure 3-36 is a map of Stiff plots for groundwater from the Molina-like sandstone unit of the Wasatch Formation. Again, red dots show the well locations that provided data for constructing the plots. The most frequent water types in Molina-like sandstone unit are: Na-SO_4 (19 locations), Na-HCO_3 (15), Na-Cl (8), Mg-Na-HCO_3 (3), and Mg-HCO_3 (3). Miscellaneous water-types were found at 23 additional Molina-like sandstone unit locations.

Na-SO_4 waters are common in both the upper and lower portions of the Molina-like sandstone unit, and are found in wells located primarily in the Dry Hollow Gulch area (Sections 27, 33, and 34 of T6S R92W, and Section 3 of T7S R92W). The origin of the sulfate is unknown but may be derived from the oxidation of bedrock containing more pyrite (FeS_2). Sulfate is the dominant anion in intermediate depth groundwater (Freeze and Cherry 1979), and the water may result from mixing of shallow and deeper formation groundwaters.

Na-Cl water-types are more common in the lower portion of the Molina-like sandstone unit (west and north edge of the outcrop area). The source of the Na-Cl is unknown, but likely represents deeper formation water or a mixture of shallow water and deeper formation water. Wells completed in the upper portion of the Molina-like sandstone unit display fewer Na-Cl water types.

5.5.17 Quality of Groundwater from the Atwell Gulch Member

Figure 5-37 is a map of Stiff plots representing Atwell Gulch groundwater. A number of distinctive water-types are visible on this figure. The most frequent water types in Atwell Gulch rocks are: Na-HCO_3 (28 locations), Na-SO_4-HCO_3 (6), Ca-Mg-HCO_3 (5), and Ca-HCO_3 (5). Miscellaneous water-types were found at 23 other Atwell Gulch member locations. Na-Cl waters are rare on Figure 5-37, showing up as relatively high-TDS waters in the Halls Gulch area at stations 704329 and 704152. A third Na-Cl water of lower TDS occurs to the north near Dry Hollow Gulch at station 703947.

The TDS of groundwater samples for wells adjacent to West and East Divide Creek are relatively low. One interpretation for this pattern is localized recharge or mixing of surface water with groundwater.

A Piper diagram of major ion chemistry in Atwell Gulch member groundwater is shown as Figure 5-38. On this plot the lower left triangle shows the proportions of cations in groundwater from this member. The data lie in a band from Ca and Mg-rich waters at the left edge of the triangle to Na-rich waters on the lower right corner of the triangle. This band can occur either from ion exchange, or from mixing of Na-rich water with one rich in Ca and Mg. It is most likely that the band shows the evolution of a Ca and Mg-rich water, undergoing ion exchange along its flowpath, to become a sodium-rich water. Data from the two lower triangles are projected into the diamond shaped region of the Piper plot, where the symbol size is scaled in proportion to calculated TDS. The diagram shows higher TDS waters on the right side of the diamond, and lower TDS waters on the left side. Because TDS tends to increase with groundwater age and residence time in the aquifer, it appears that young, low TDS, Ca and Mg-rich waters are evolving into higher TDS, sodium-rich waters in the Atwell Gulch member.

Piper diagrams for groundwater from the Shire member, and from the Molina-like sandstone unit, look very similar to the Atwell Gulch member Piper diagram just described.

5.5.18 Quality of Groundwater from Alluvium

Figure 5-39 is a map of Stiff plots for alluvial groundwater. All of the sample locations are from a small area by the West Divide Creek seep in T7S R92W S12. The legend shows that the width of the Stiff plots is proportional to the concentrations of 6 major ions. Most of the alluvial waters are Ca-HCO_3 and/or Na-HCO_3 water-types, including: Ca-HCO_3 (7 locations), Na-Ca-HCO_3 (4), Ca-Na-HCO_3 (4), Na-HCO_3 (3), and Ca-Na-Mg-HCO_3 (1). Na-Cl and Na-SO_4 water-types were not identified in alluvial water wells.

5.6 SURFACE WATER QUALITY INTERPRETATIONS

The following text sections discuss the geochemistry and quality of surface waters in the study area. The data are initially viewed from a larger study area perspective to determine regional trends, then the data are classified and examined by surface-water-type (e.g., spring water), or by the geology of the water source.

Figure 5-40 is a location map which shows surface water sampling locations selected for discussions of major ion chemistry. Locations are shown by surface water type (e.g., pond versus stream). Figure 5-40 is a reference map for the surface water quality discussions.

5.6.1 Regional Variations in Surface Water Quality

Surface water quality generalizations are constructed by evaluating the analytical data on a site-wide basis. This is done in the following subsections by using a variety of approaches: identification of water-types, scatterplots, concentration bubble maps of concentrations and ion ratios, stable isotope chemistry, cluster analysis, principal components analysis, descriptive statistics, and data comparisons with water quality standards.

5.6.2 Water-Types and Major Ion Chemistry of Surface Water

Surface water analytical data with less than 10 percent charge balance error led to the selection of 61 sampling locations for evaluation of major ion chemistry. Out of the 61 sampling sites, 22 are associated with alluvium, 18 are on the Shire member of the Wasatch Formation, 9 are on the Molina-like sandstone unit, and 12 are on the Atwell Gulch member. Spring waters were sampled at 33 of the 61 sites, stream waters were sampled at 18 sites, and 10 locations represent pond waters.

Few dissolved (filtered) surface water quality data were available, therefore, it was necessary to use concentrations for analytes in unfiltered samples for determining major ion chemistry. The most common water-types in surface water are bicarbonate waters. Water-types with the highest frequency are: Mg-HCO_3 (11 occurrences), Na-HCO_3 (9), Ca-Na-HCO_3 (7), Ca-Mg-HCO_3 (7), and Ca-HCO_3 (7). Other miscellaneous water-types (most dominated by Na) were found at 20 other stations.

The highest frequency water-type in pond waters is Ca-Mg-HCO_3, followed by Mg-Na-HCO_3, and Mg-HCO_3. Water-types with the greatest frequency in springs are: Mg-HCO_3 (9 stations), Ca-HCO_3 (5), and Ca-Mg-HCO_3 (4). Various other water types were found at 15 other spring locations. Stream waters in the study area are often Na-HCO_3 waters (5 occurrences), or Ca-Na-

HCO_3 (5), or Na-Ca-HCO_3 (3). Other less common water-types were found at 5 additional stream sampling locations.

Figure 5-41 ranks the water-types in surface waters by the mean concentration of calculated TDS. The three highest-TDS water-types shown in the left-hand side of the figure are predominantly Na-SO4 or Na-Cl waters, similar to what was seen in groundwater (Figure 5-5). The remaining water-types on the middle and right-hand portions of the figure are all low-TDS (<900 mg/L) metal bicarbonate waters, again very similar to groundwater. Although there are some Na-rich low-TDS surface waters on Figure 5-5, most of the low-TDS waters are Ca or Mg bicarbonates.

Figure 5-42 plots symbols whose size are scaled to the TDS of the water. The symbol color is coded to the water-type. Thirdly, the symbol shape is keyed to the lithology spatially associated with the surface water. As an example, the large brown triangle near the southeast corner of the map, is a stream sample with a Na-Cl water-type with a TDS near 1,700 mg/L. The triangle indicates that the underlying rocks are of the Atwell Gulch member. Some generalizations from inspection of Figure 5-42 follow.

- The number of water-types are fewer than for groundwater (Figure 5-6), but the number of surface water locations is about one-fourth the number of groundwater locations available for major ion chemistry.
- The TDS of the surface waters has a lower range (up to 3000 mg/L) than groundwater (up to 6000 mg/L).
- The larger creeks seem to have low-TDS waters (i.e. Divide Creek).
- An area of fairly high TDS spring waters is located between Hunter Mesa Road and Mamm Creek Road (location 704385).

Figure 5-43 is a map showing Stiff plots for surface water samples. Red dots show the sampling locations that provided data for constructing the map. A variety of water-types are visible on this figure. The highest-TDS water-type is a Na-SO_4 water and is seen as a distinctively shaped Stiff plot at station 704469 west of Dry Hollow Creek. An unusual Na-Cl rich water-type is observed in the extreme southeast corner of Figure 5-43 at station 704429. Na-Cl groundwater was also described in Atwell Gulch rocks near this area. Note that the surface water on Grass Mesa at station 704466 is a Mg-Na-HCO_3 pond water. This pond water has a higher TDS (probably from evaporation), and a different chemistry than the Shire groundwater samples evaluated in this area (see Figure 5-34). Spring water at Grass Mesa station 704443 is a Na-Mg-HCO_3 water similar to the Shire groundwater in this area, except station 704443 has a higher TDS.

Calculated TDS was regressed against TDS measured in surface water samples (Figure 5-44). The fit is very good except for a single point with a measured TDS of about 1,700 mg/L and a calculated TDS of only 600 mg/L. This difference could result from dissolved or suspended solids in the water sample, which was unaccounted for in the major ion analyses.

5.6.3 Cluster Analysis and PCA of Surface Water Major Ions

Cluster analysis of variables was performed on the data selected for describing the major ion chemistry of unfiltered surface water. Variables selected for clustering were the major ions: Ca, Mg, Na, K, chloride, bicarbonate, and sulfate. The analysis used the mean concentrations (in meq) of these ions from 61 sampling locations. The objective was to determine if cluster analysis would identify the same water-types that were identified by the AquaChem software based on ion abundances in meq units.

Figure 5-45 displays the results of cluster analysis as a dendrogram. This figure predicts Ca-Cl, Mg-HCO_3, and Na-SO_4 water-types, and complex Mg-Na-HCO_3-SO_4 waters. It correctly predicts that potassium is the least important of the major ions in determining water-types. However, the cluster analysis is not very satisfactory for identifying water types, because Ca-Cl surface waters have not been identified in the study area, and Na-SO_4 surface waters are relatively rare. We know from analytical data that Mg-HCO_3, Na-HCO_3, Ca-HCO_3, and combinations of Ca, Mg, Na, with HCO_3 are the most common water-types.

PCA was performed on 8 input variables (components) representing the major ion composition of surface waters. A correlation matrix was used in the PCA, because the major ions were in meq/L units, while TDS data were in mg/L units. Figure 5-46 is a scree plot of the PCA output, and Table 5-15 contains additional output parameters from the PCA. Principal components that each account for more than 10 percent of the variance are: Ca (component 1 at 53 percent of the variance), Mg (component 2 at 18 percent), and Na (component 3 at 12 percent). Minor components, potassium and sulfate each account for 7 percent of the variance, while bicarbonate (component 6) was a minor contributor to variance at only 2.6 percent. Chloride and TDS each contributed less than 0.2 percent. Bicarbonate water-types predominate in surface water samples and therefore may contribute little to variance between samples.

5.6.4 Graduated Symbol Maps of Analyte Concentrations in Surface Water

Numerous graduated symbol maps have been prepared of analyte concentrations and ion ratios in surface water samples. These maps are discussed below.

Field-measured pH values for surface waters are posted on Figure 5-47 as mean concentrations. The legend for this figure shows that the pH values range from 7.0 to about 9.0 S.U. One of the higher pH locations is station 703948. There have been 64 pH measurements of water at location 703948. The highest of these measurements is 9.43 measured on 3/18/05, and most of the measurements at this station are in the pH range of 8.0 to 9.0.

Fluoride ion concentrations in unfiltered surface water samples are mapped on Figure 5-48. This figure indicates that fluoride concentrations are generally low in surface water samples. Out of 294 fluoride measurements, 293 are at or below the 4 mg/L MCL. The highest fluoride concentration is 8 mg/L in spring water at location 704324 in the southeast corner of the study area.

Figure 5-49 shows the range of nitrate ion concentrations (as N in mg/L) in surface waters. Out of more than 300 measurements of nitrate the highest concentrations have come from location 703937, a spring located on the east edge of the study area. Twelve nitrate analyses of this spring water have varied widely from nondetect (<1.3 mg/L) up to 70.8 mg/L, during the period January 2003 to July 2005. The median concentration at the spring is 43.5 mg/L. The drinking water MCL for nitrate is 10 mg/L. An agricultural source of nitrate is suspected, such as a nearby fertilizer application. Ignoring station 703937, the next highest nitrate concentration is 11.3 mg/L at another spring, station 704027, located southeast of Grass Mesa in Sec 10 T7S 93W.

Selenium concentrations in unfiltered surface water are generally low (Figure 5-50). More than 280 selenium concentrations have been measured in surface water, but only three values have exceeded the drinking water MCL of 0.05 mg/L. The highest selenium concentration is 0.22 mg/L in stream water at location 703916. The Colorado basic surface water standard for selenium varies for aquatic life and agriculture, but guidance values are between 0.004 and 0.020 mg/L. Pond waters at stations 704420 and 704501 have selenium concentrations of 0.056 and 0.054 mg/L, respectively.

Few data for arsenic concentrations in surface water are available. Figure 5-51 plots only 11 measurements at 10 locations. Pond location 704147 had one concentration (0.089 mg/L) that appeared to exceed the MCL of 0.05 mg/L, but a second pond sample found only 0.004 mg/L of arsenic. None of the other 9 locations had arsenic concentrations above the MCL.

Benzene, toluene, ethyl benzene, and xylenes (BTEX constituents) and other organic compounds have been detected in surface waters. Benzene has been found at or near West Divide Creek at the seep area (Sec 12 T7S 92W). A graduated symbol map was not constructed for benzene because all of the detected concentrations are located at the seep area. About 30 measurements exceeded the 5 μg/L benzene MCL, and most of these exceedances are at three locations: 704094, 704093, and 704095. The highest benzene concentrations reached 360 μg/L at stream station 704093 on December 12, 2004. Also very high was the 150 μg/L benzene at seep 704279 on April 11, 2005. This seep is located near the West Divide Creek seep area.

The dataset has two detections of ethylbenzene in surface water above 5 μg/L. One detection is 16 μg/L at stream 704093 on December 20, 2004, and the other is 10 μg/L at seep 704279 on April 11, 2005. The drinking water MCL for ethylbenzene is 700 μg/L.

Toluene has also been detected in surface water about 20 times out of more than 800 measurements. All of the toluene concentrations measured to date have been far below the MCL of 1000 μg/L. The highest toluene concentrations in the dataset are: 130 μg/L at station 704093, 100 μg/L at 703888, 62 μg/L at 704279, and 28 μg/L at 704101.

Various isomers of xylene have been analyzed in study area surface waters. Meta and para-xylene concentrations seem to be the highest based on available data. However, out of more than 1,570 analyses of xylene isomers only about one dozen detections have been reported. The highest detections are for meta and para-xylene: 110 μg/L at station 704093 on 12/20/04, 65 μg/L at 704279 on 4/11/05, 17 μg/L at 703888 on 4/2/04, and 17 μg/L at 704093 sampled on 12/20/04. The MCL for total xylenes is 10,000 μg/L.

There are more than 800 analyses of methane in surface water samples, and more than 600 of these have detected methane. The majority of these samples are from the West Divide Creek seep area located in Section 12 of T7S R92W. Although methane appears to be widespread in surface waters, only three sampling locations have had concentrations above 1,000 μg/L. These high methane concentrations are: 12 mg/L sampled on 12/20/04 at station 704093, 11 mg/L sampled 4/11/05 at station 704279, 1.5 mg/L at 704094 on 12/2/04, and 1.2 mg/L also at 704094 on 11/2/04.

5.6.5 Stable Isotope Chemistry of Surface Water

Figure 5-52 plots stable isotope ratios for carbon and hydrogen in methane associated with surface water samples. By referring to Table 5-1 and Figure 5-3, the isotope ratios of Figure

5-52 may be classified as indicating methane of thermogenic origin, or of biogenic (microbial) origin. The curved bands on Figure 5-53 denote these classifications. Notice that stations with thermogenic methane (e.g., 704093 and 704279) were previously reported to have BTEX compounds, and elevated methane concentrations above 1 mg/L in their water. Thus the detection of BTEX in water may be one of the simplest indicators of water contamination from nearby gas wells.

Surface water station 703895 is classified as a pond on West Divide Creek in T7S R92W Sec 12. The isotopic ratios of water at station 703895 indicate that the methane may have a mixed origin, partly biogenic and partly thermogenic.

5.6.6 Descriptive Statistics and Comparisons Against Water Quality Standards

Table 5-16 contains descriptive statistics for surface water quality. The statistics are grouped by type of surface water (i.e., pond, stream, or spring), and then by analyte. Besides mean concentrations, the table shows the percentage of detected concentrations, three sets of water quality standards, and the percentages of the data that exceed each standard. In Table 5-16 the code “MCL” refers to the EPA drinking water maximum contaminant level or MCL. Code “COGW” means Colorado basic groundwater standards for drinking water, and “COSW” refers to Colorado basic surface water standards for drinking water supply. For example, nitrate in pond waters did not exceed any of these standards, but nitrate concentrations in spring water exceeded each standard about 12 percent of the time.

The percentage of wells that exceed Colorado basic surface water standards is summarized in Table 5-17.

5.6.7 Hardness of Surface Water

Surface water hardness is of concern if the water is to be used for household uses. Hard water causes scaling problems in hot water heaters and excessive consumption of soaps. Figure 5-53 is a quantile plot of calculated hardness values for 61 surface water locations. It shows that most surface waters are very hard, with a median hardness of about 360 mg/L as $CaCO_3$. More than 90 percent of these surface waters fall in the hardness range of 210 to about 700 mg/L.

5.6.8 Quality of Spring Water

Data identified as coming from springs are classified as surface water in this report. It could be argued that if spring water is carefully sampled by peristaltic pump immediately as it emerges on the surface, or from a driven pipe before it contacts the atmosphere, then its properties may be closely similar to those measured in nearby groundwater wells screened in the same lithology. However, many of the “spring” analyses in the dataset may derive from samples collected from shallow depressions, or which otherwise have altered chemistry from processes such as: gas exchange, precipitation, oxidation from contacting air, or uptake of nutrients by surficial plants and organisms.

Figure 5-54 is a piper diagram of the major ion chemistry of spring waters. Notice that the lower left-hand triangular region holds many scattered points, rather than a nice linear band as was seen earlier for groundwater (see Figure 5-37). The diamond shaped region in Figure 5-54 also shows less variation in TDS than was seen for groundwater.

A Schoeller plot of spring water (Figure 5-55) shows that most of the spring waters have low chloride and high bicarbonate concentrations. Calcium and magnesium typically occur at higher concentrations than sodium.

5.6.9 Quality of Stream Water

The Schoeller plot of stream waters is presented as Figure 5-56 for comparison with the spring water (Figure 5-55). Both plots are very similar.

There are USGS gauging stations on Beaver Creek (located outside the west study area boundary), and at Raven Station on West Divide Creek (located southeast of the study area). The USGS has collected water quality data at these stations in addition to gauging stream flow. Although plots are not shown for these stations, their water quality data were examined. The pH of water from both creeks is very similar and in the range 7.9 to 8.6 S.U. TDS appears to be higher in Beaver Creek than at Raven Station, based on concentrations of sodium, chloride, and sulfate. Sodium concentrations in Beaver Creek are 110 to 190 mg/L, while those at Raven are consistently less than 40 mg/L. Sulfate concentrations in Beaver Creek are 130 to 170 mg/L, while those at Raven are consistently less than 40 mg/L. Chloride concentrations in Beaver Creek are 150 to 290 mg/L, while those at Raven are very low, usually less than 10 mg/L. These chemistry differences reflect different water sources for Beaver Creek and West Divide Creek.

5.6.10 Quality of Pond Water

Figure 5-57 is a Schoeller plot for pond waters. The number of pond locations is low in comparison to streams and springs. However, Figure 5-58 looks very similar to the Schoeller plots for streams and springs.

5.7 WATER SOURCES AND MIXTURES OF WATERS

Stiff diagrams and Piper plots were used to evaluate and compare surface and ground water signatures and potentially understand evolution of water-types. Figures 5-58 through 5-61 are Stiff diagrams constructed from major cation and anion data using samples from creeks (USGS stream sample data), COGCC surface water data, Wasatch water well data, and produced water data, respectively. Figure 5-62 is a Piper plot of all of the combined data.

There are several sources of surface and groundwater in the study area: precipitation events (rain or snow fall), stream or river water, and groundwater from various depths beneath the area. Most sources of water are a combination of surface water and groundwater. Although springs, seeps, and ponds are considered surface water samples, the source of the water is generally from groundwater, or surface water that has migrated through the ground for some distance and then surfaces at ground level. River water is a combination of surface runoff from precipitation events and groundwater inflow to the stream. Groundwater from deep bedrock water wells may have little resemblance to surface water, but shallow groundwater present near a water body can resemble the surface water chemistry.

Water recovered from the production of gas from producing wells is termed produced water. Produced water is stored in aboveground storage tanks (ASTs) on the well pad where it is separated from the gas and condensate. The produced water is typically hauled off by a tanker truck for treatment and disposal, but if there is sufficient water generated in the area, the water may be transported by pipeline to the treatment facility. Produced water represents the deepest source of water that is currently available for sampling.

URS obtained produced water sample analyses from documents available on the COGCC on-line database. Analyses were located for 15 gas wells, all of which are located within the study area. Produced water is generally high in TDS (10,000 to 20,000 mg/L), and the primary water type is sodium chloride (Na-Cl). However several samples had bicarbonate as the dominant or co-dominant anion (Na-HCO3-Cl water type).

The USGS stream data (Figure 5-58) is from water quality samples collected by the USGS at gauging stations at two Divide Creek locations (Raven station located south of the study area and Divide Creek mouth near Silt) and a station on Beaver Creek located immediately west of the study area. The samples from alluvial and bedrock aquifer water wells, and surface waters (springs, ponds, and rivers) were selected to provide a “representative” collection of known water types.

Stiff diagrams for the three USGS gauging station locations are all different shapes, but display low TDS concentrations (see milliequivalent scale for each diagram). The change in cation and anion concentrations and water types between the Raven station (upstream) and the Divide Creek station (downstream) have little in common, and suggests inflow of other surface water and/or groundwater into Divide Creek occurs between the two stations.

Stiff diagrams for the surface water samples (Figure 5-59) display a wide variety of shapes, reflecting different sources of water. Three of the samples resemble the USGS creek samples, but the other three diagrams suggest mixing occurred between low TDS bicarbonate waters with higher TDS concentration groundwater containing sodium, chloride, and/or sulfate (Facility numbers 704429, 704469, and 704519).

The Stiff diagrams for the bedrock water wells (Figure 5-60) also display a wide range of shapes. Typical diagrams for the Grass Mesa area (Shire Member of the Wasatch Formation) are typically low TDS sodium-bicarbonate waters (facility numbers 703989 and 704047) reflecting a recent, shallow source of water (i.e. precipitation infiltration). However, water samples from several bedrock wells flanking Grass Mesa show a distinctly different pattern dominated by sodium-chloride and a higher TDS concentration (703259 and 704061). The sodium-chloride water type is typical of produced water. Stiff diagrams for samples obtained from water wells completed in the Molina-like sandstone unit show three distinct patterns: 1) a lower TDS sodium-bicarbonate water type, 2) a higher TDS sodium-sulfate water type, and 3) a sodium-chloride water type. The sodium-sulfate water type is the dominant water type in the Dry Hollow Gulch region of the study area. Water wells completed in the Atwell Gulch Member show two main patterns: 1) a low TDS sodium and/or calcium-bicarbonate water type, and 2) a sodium-chloride water type with higher TDS.

Stiff diagrams for produced water samples are shown on Figure 5-61. There are two main patterns: 1) a sodium-chloride, high TDS water type, and 2) a sodium-bicarbonate-chloride water type with a lower TDS concentration.

Based on review of these Stiff diagrams and the maps of Stiff diagrams presented earlier in Section 5, there are four primary water types in the study area, as well as mixtures of all of these types:

- Low TDS calcium-bicarbonate (alluvial or shallow bedrock depth or near streams and young surface water)
- Low TDS sodium-bicarbonate (bedrock water wells located away from major streams)
- Moderate TDS sodium-sulfate (bedrock water wells located near Dry Hollow Gulch)
- High TDS sodium-chloride (bedrock water wells flanking Grass Mesa, south of Dry Hollow Gulch, West Divide Creek seep area, and the southeast corner of the study area, and produced water from gas reservoirs in the Mesaverde Group)

A Piper diagram with major cation and anion data for approximately 40 water samples is shown in Figure 5-62. The USGS creek data and other surface water samples generally plot in the calcium to sodium (cation) and bicarbonate to sulfate (anion) areas of the diagram. The bedrock (Wasatch Formation) water well data shows a trend from calcium and sodium cations to predominately sodium, and the anion data plots primarily in the bicarbonate then to the sulfate and chloride areas. The produced water samples clearly plot in the sodium chloride portions of the Piper diagram, as do several of the water wells completed in the Wasatch Formation.

The Piper diagram shows a trend in the cation data that suggests an evolution from calcium, sodium, and magnesium as the dominant cation to just sodium.

5.8 SUMMARY

The scope of the water quality section of the project was to compile, review, and interpret existing groundwater and surface water quality data for the study area. The primary objective of the task was to characterize water quality conditions in the alluvial and bedrock aquifers, and seek geochemical evidence of potential impacts to water quality resulting from natural gas exploration and other anthropomorphic activities.

The vast majority of existing water quality data is located in the COGCC database. The data was generated either by work conducted by COGCC to address various complaints in the area over time, or by consultants working for EnCana or BBC who collected baseline water quality data from existing water wells and existing surface water bodies (i.e., streams, springs, ponds) immediately prior to drilling gas wells in some locations. In addition, a large volume of data have been collected for the investigation and ongoing remediation of the West Divide Creek gas seep. However, both BBC and EnCana have collected baseline samples in other areas during the past few years. This baseline data was submitted to COGCC by Cordilleran consultants upon request by URS and approval by EnCana and BBC. COGCC imported the data into their existing database and then extracted the data for URS to use in this study.

Water quality data was integrated with lithologic (e.g., alluvial or Wasatch aquifer), well depth, and specific capacity data for the water well completions, To integrate the data, URS attempted to index the water quality locations having GPS survey coordinates to locations of permitted water wells maintained by the SEO. Only about two-thirds of the locations could be reliably correlated.

For major ion chemistry, the existing data was checked by calculating the charge balance for cations and anions. A total of 220 groundwater sample and 61 surface water sample locations were selected for evaluation based on a calculated maximum charge balance error of plus or minus 10 percent. Most sample locations have been sampled only a few times; and evaluation of temporal concentration trends was not performed.

URS evaluated the major ion data to determine water types (e.g., Na-Cl type), using Piper plots, Schoeller plots, and Stiff plots. Principal component analysis (PCA) and cluster analysis were performed on the major ion datasets to evaluate the variance in water types.

Data for stable isotope chemistry of both surface water and groundwater was also evaluated and interpreted to distinguish between biogenic and thermogenic methane origins at several locations. Concentrations of many major ions and metals were summarized and compared to Colorado basic groundwater and surface water standards to determine the percentage of water samples in exceedances of relevant standards. Water hardness and sodium adsorption ratio (SAR) were also evaluated.

Graduated symbol maps were also constructed using ArcMap to show the variation in select individual analytes (organic and inorganic) concentrations and analyte ratios across geographic areas. Particular attention was directed toward evaluation of water well locations relative to gas well drilling activity where concentrations of dissolved methane were above 1 or 2 mg/L, and wells where fluoride, selenium, and TDS were highest and/or the sodium-chloride and sodium-sulfate water types were present.

5.8.1 Groundwater Quality

Of the 220 groundwater sample locations suitable for major ion evaluation, 195 wells are domestic wells, 21 are monitoring wells located at the West Divide Creek seep area, and 4 are irrigation wells. The inferred geology for the well completions consists of 67 locations in the Atwell Gulch member, 62 locations in the Shire member, 72 locations in the Molina-like sandstone unit, and 19 alluvial locations. There are very few water wells located on Hunter Mesa and the southwest quadrant of the study area.

Sodium is the dominant cation and bicarbonate is the dominant anion at more than 60 percent of the locations. The most frequent water types are Na-HCO_3 (49 locations), followed by Na-SO_4 (22), Na-SO_4-HCO_3 (16), Na-Cl (15), with various Ca and/or Mg-HCO_3 waters accounting for 41 more locations. Groundwater with higher TDS values (>1,500 mg/L) is generally of the Na-Cl or metal sulfate type (i.e., Na- SO_4). Metal bicarbonate water types comprise samples with lower TDS concentrations (<1,000 mg/L). Principal component and cluster analysis of major ion data offered little in explaining which ions were most influential for explaining water type variances.

The sodium-sulfate water type occurs primarily in the Dry Hollow Gulch area, where Dry Hollow Road enters the narrow portion of the stream valley (Sec 3 T7S92W and Sec 33 and 34 of T6S 92W), and Na-Cl water types are also found in this area, specifically at well locations just downstream from the start of the narrow valley. It is speculated that these high-TDS waters may be derived from deep groundwater of higher salinity, perhaps diluted by mixing with shallow groundwater. The deep groundwater may migrate toward the surface by migrating along fractures or fracture zones related to larger structures like the Divide Creek anticline.

This interpretation seems to fit the Na-Cl water type better than the Na-SO_4 water type. Sulfate is not typically associated with deeper groundwater associated with natural gas or other hydrocarbons. The hydrocarbons serve as energy sources to bacteria, which consume oxygen and other electron receptors and drive the water chemistry to reducing conditions. Under reducing conditions, sulfate-reducing bacteria consume sulfate present in the groundwater to oxidize carbon sources, thereby decreasing sulfate concentrations in deeper groundwater. However, the source of sulfate to groundwater may originate from an intermediate depth where a mineralogic source of Sulphur is located, or geochemical conditions favor the occurrence of sulfate. URS did not locate and water quality data or wells that are completed in the deeper portions of the Wasatch Formation. The upper Molina-like sandstone unit is thick and relatively massive in this area of Dry Hollow Gulch, and there are a number of linear structures mapped in this location that suggest the presence of fracture zones. The area may have a more dynamic groundwater flow regime caused the presence of more interconnected fracture systems. Deeper Na-Cl type water may move up along deeper fractures.

It is speculated that most shallow groundwater in the study area starts out as metal bicarbonate waters (Ca-HCO_3 or Mg-HCO_3 water), which evolve and pick up sodium ions through ion exchange processes. As the sodium increases, the residence time of the water is increasing, and the TDS also increases. Some of the Ca, Mg, and bicarbonate may also be lost as the water "ages" through precipitation of Mg-bearing calcite.

The majority of the pH data is within a normal range of 6 to 9 standard units. The highest values of nitrate were observed in two irrigation water wells, with maximum values of 131 and 163 mg/L. The maximum concentration in a domestic well was 105 mg/L. The EPA drinking water MCL is 10 mg/L.

Fluoride concentrations in groundwater are highest (approximately 10 mg/L) in the area around the nose of the Divide Creek anticline (Sec 34 T6S 92W), and may indicate the presence of water from a deeper formation, or coincide with a localized source of fluoride. The EPA drinking water MCL for fluoride is 4 mg/L.

Selenium concentrations also exceeded groundwater standards in several domestic water wells. The MCL is 0.05 mg/L, and groundwater concentrations ranged as high as 1 mg/L.

Benzene and other hydrocarbon constituents were detected in a number of monitoring wells in the West Divide Creek seep area. Benzene was not detected in domestic water wells anywhere in the study area.

Based on stable isotope ratios, many of the domestic wells where these analyses were conducted appear to contain biogenic methane. However, three domestic wells have ratios which plot in an area located between biogenic and thermogenic methane. These three wells have methane of uncertain origin, which may be gas from multiple sources. Where stable isotope data is available for monitoring wells located in the West Divide Creek seep area, analysis suggests the methane is of thermogenic origin except for one. Approximately 20 domestic water wells have been sampled where methane concentrations exceeded 2 mg/L. No stable isotope data was available for these wells, and they should be resampled and analyzed for stable isotope concentrations to allow initial determination of whether the methane is of biogenic or thermogenic origin.

Groundwater samples exceeded the Colorado basic groundwater standards for a number of constituents. Ten to 15 percent of the samples from domestic wells exceeded the standard for chloride, fluoride, nitrate, or selenium. The standard for iron and manganese was exceeded by about 25 percent of the domestic well samples. For irrigation wells, the standard was exceeded for roughly 20 percent of the samples for chloride, fluoride, or iron, and almost 50 percent of the samples exceeded the selenium and sulfate standards. Sixty-six percent of the irrigation wells samples exceeded the nitrate groundwater standard.

About one-half of the groundwater samples were considered very hard, with a calculated hardness greater than 300 mg/L as $CaCO_3$. Three irrigation well samples were classified for sodium adsorption ratio (SAR). The results showed a class C3-S3 code, indicating high salinity and high sodium water that may not be suitable for irrigation with restricted drainage and requiring special soil management for good drainage and leaching.

Wells located on Grass Mesa are all completed in the Shire member of the Wasatch Formation. Wells in this area generally had the lowest TDS values and bicarbonate is the dominant anion. The low-TDS concentrations suggests that the Grass Mesa groundwater originated from local infiltration of rainwater and snow-melt. By contrast, high-TDS Na-Cl water-types are seen to occur both east and west of Grass Mesa, but not on the mesa. These locations are located along a linear aeromagnetic anomaly, and may reflect upward movement of deeper formation waters. The high-TDS water probably has a deeper source because TDS, sodium, and chloride concentrations often increase with the age or residence time of the groundwater. The most frequent water types in Shire rocks are: $Na\text{-}HCO_3$ (9 sampling locations), $Ca\text{-}Mg\text{-}HCO_3$ (8), $Mg\text{-}HCO_3$ (8), $Mg\text{-}Ca\text{-}HCO_3$ (7), and $Mg\text{-}Na\text{-}HCO_3$ (5).

The most frequent water types in the Molina-like sandstone unit are $Na\text{-}SO_4$ and $Na\text{-}HCO_3$.Na-Cl water-types are more common in the lower portion of the Molina-like sandstone unit (west and north edge of the outcrop area). The source of the Na-Cl is unknown, but likely represents deeper formation water or a mixture of shallow water and deeper formation water. Wells completed in the upper portion of the Molina-like sandstone unit display fewer Na-Cl water types. $Na\text{-}SO_4$ waters are common in both the upper and lower portions of the Molina-like sandstone unit in the area of Dry Hollow Gulch where the valley narrows in Section 3 T7S R92W.

The most frequent water types in Atwell Gulch rocks are $Na\text{-}HCO_3$ and $Na\text{-}SO_4\text{-}HCO_3$ (6). Na-Cl waters are rare but occur as relatively high-TDS waters in the Halls Gulch area and north near Dry Hollow Gulch.

The TDS of groundwater samples for wells adjacent to West and East Divide Creek are relatively low. One interpretation for this pattern is localized recharge or mixing of stream water with groundwater.

A Piper diagram of major ion chemistry in Atwell Gulch groundwater can be used to illustrate the evolution of shallow groundwater in the study area. It appears that young, low TDS, Ca and Mg-rich waters are evolving into higher TDS, sodium-rich waters in the Atwell Gulch member.

Piper diagrams for groundwater from the Shire member, and from the Molina-like sandstone unit look very similar to the Atwell Gulch Piper diagram.

Alluvial aquifer water samples were all located in the West Divide Creek seep area. The primary water types are $Ca\text{-}HCO_3$ and/or $Na\text{-}HCO_3$ water-types. Na-Cl water-types may be nonexistent in alluvial waters, although other stream drainages with alluvial groundwater need to be sampled to confirm this.

5.8.2 Surface Water Quality

Major ion chemistry was evaluated from 61 surface water samples that had a charge balance within plus or minus10 percent. Out of the 61 sampling sites, 22 are associated with alluvium, 18 are on the Shire member of the Wasatch Formation, 9 are on the Molina-like sandstone unit, and 12 are on the Atwell Gulch member. Spring waters were sampled at 33 of the 61 sites, stream waters were sampled at 18 sites, and 10 locations represent pond waters.

The most common water-types in surface water are Mg and Na bicarbonate waters.

The highest frequency water-type in pond waters is Ca-Mg-HCO_3, followed by Mg-Na-HCO_3, and Mg-HCO_3. Water-types with the greatest frequency in springs are: Mg-HCO_3 and Ca-HCO_3. Stream waters in the study area are often Na-HCO_3 waters or Ca-Na-HCO_3.

The highest TDS water-types are predominantly Na-SO4 or Na-Cl waters, similar to what was seen in groundwater. The low-TDS (<900 mg/L) waters are of a metal bicarbonate type, again similar to groundwater. Most of the low-TDS waters are Ca or Mg bicarbonates.

The number of water-types are fewer than for groundwater, but the number of surface water locations is about one-fourth the number of groundwater locations available for major ion chemistry.

The TDS of the surface waters has a lower range (up to 3000 mg/L) than groundwater (up to 6000 mg/L).

The highest-TDS water-type is a Na-SO_4 water located west of Dry Hollow Creek. One Na-Cl rich water-type is observed in the extreme southeast corner of the study area, and a Na-Cl groundwater was also described in Atwell Gulch rocks near this area.

Field-measured pH values for surface waters range from 7.0 to about 9.0 S.U.

Only one surface water sample exceeded the 4 mg/L MCL for fluoride. The highest fluoride concentration is 8 mg/L from spring water located in the southeast corner of the study area. Fluoride concentrations in groundwater were also elevated in this area.

Nitrate concentrations from samples obtained at a spring located on the east edge of the study area have varied widely from nondetect (<1.3 mg/L) up to 70.8 mg/L, during the period January 2003 to July 2005. An agricultural source of nitrate is suspected, such as a nearby fertilizer application. The next highest nitrate concentration is only 11.3 mg/L at another spring located southeast of Grass Mesa in Section 10 T7S 93W. The drinking water MCL for nitrate is 10 mg/L.

Only three surface water samples have exceeded the MCL of 0.05 mg/L for selenium. The highest selenium concentration is 0.22 mg/L in stream water from Dry Hollow Creek. Two pond water samples have selenium concentrations of 0.056 and 0.054 mg/L, just over the standard.

None of the nine locations sampled and analyzed for arsenic had concentrations above the MCL.

Benzene has only been found in surface water samples obtained from near the seep at West Divide Creek. The highest benzene concentrations reached 360 μg/L in a seep sample.

Surface water hardness is a concern if it will be used for domestic purposes. Most surface waters are very hard, with a median hardness of about 360 mg/L as $CaCO_3$. More than 90 percent of these surface waters fall in the hardness range of 210 to about 700 mg/L.

Most of the spring, stream, and pond waters are low in chloride and high in bicarbonate ion.

USGS gauging stations are located outside of the study area on Beaver Creek (located outside the west study area boundary), and at Raven Station on West Divide Creek (located southeast of the study area). Water quality data is available for these stations. The pH of water from both creeks is very similar and in the range 7.9 to 8.6 S.U. TDS appears to be higher in Beaver Creek than at Raven Station, and concentrations of sodium, chloride, and sulfate are all higher at Beaver Creek than at the Raven station. The chemistry differences reflect different water sources for Beaver Creek and West Divide Creek.

5.8.3 Methane in Groundwater and Surface Water

Based on the available data, it appears that groundwater concentrations of methane in the western portion of the study area are lower than wells in the eastern half of the study area and range from nondetect to 2 mg/L. Most of the water samples did not have methane concentrations above reporting limits. When methane was detected, it was at very low concentrations. The origin of the methane at these low concentrations may be biogenic or thermogenic. There are very few water wells located on Hunter Mesa, and a great number of gas wells. Groundwater quality for a large portion of this area is essentially unknown.

Several areas in the eastern portion of the study area contain methane in groundwater and surface water. Based on work performed by COGCC, in the vicinity of the West Divide Creek gas seep and the G33 pad area groundwater and surface water have been impacted by thermogenic methane related to gas development activities. However, a number of domestic water wells in the eastern and southeastern portion of the study area have elevated methane concentrations (>2 mg/L) and the origin of the methane is unknown.

Another area impacted by methane in groundwater is the southeast portion of the study area. Extensive water sampling from water sources in the area has detected some of the highest concentrations of methane. A number of domestic water wells located in the southeast portion of the study area contain concentrations of methane above 2 mg/L although the origin of the methane is largely unknown (i.e., biogenic or thermogenic). Although there has been relatively little drilling in the vicinity of the Divide Creek area, some of the older wells in the Mamm Creek field were drilled in this area. The potential exists for releases of petroleum hydrocarbons and/or high TDS fluids to have occurred from inadequately plugged and abandoned wells in this area. The PhilPott JO #1 well located in the NWNW Section 36, T7S, R92W was drilled to a total depth of 5,425 feet and then plugged and abandoned in 1966. The plugging record indicted that the annulus was still under pressure during plugging. Almost 30 years later the landowner discovered that the well was leaking oil and water to the surface. In 1994 the well was plugged again. It seems that the well could have been leaking for almost 30 years, and a large quantity of gas and reservoir fluids could have been released to the shallow subsurface in this area.

Table 5-1
Natural Gas Compositions in the Piceance Basin

Producing Interval	Methane % by volume	Carbon Dioxide % by volume	C1/(C1 to C5)	δ ^{13}C per mil
Green River Formation	86.3 to 92.7	0.7 to 8.4	0.946 to 0.963	-46.3 to -41.5
Wasatch and Fort Union Formations	82.0 to 92.1	0.1 to 1.8	0.917 to 0.976	-36.8 to -27.0
Williams Fork	24.2 to 93.1 (usually >70%)	0.0 to 22.4	0.794 to 0.996	-43.6 to -32.2 (ignores two apparent typos from Johnson & Rice (1990))
Coal Beds of Cameo Fairfield Coal Zone	50.9 to 86.5	2.0 to 14.3	0.978 to 0.990	-42.9 to -29.1

Table based on data from Johnson and Rice (1990).

Table 5-2
Categories of Water Hardness

Water Hardness	Mg/L as $CaCO_3$
Soft water	<=75
Moderate hardness	>75 to 150
Hard water	>150 to 300
Very hard water	>300

Table data source is NDWC (2005).

Table 5-3
PCA Output Parameters for Major Ions in Groundwater

Results for: GW Garfield.MTW
Principal Component Analysis
Eigenanalysis of the Correlation Matrix

Eigenvalue	3.0368	2.0698	1.0314	0.8524	0.7552	0.2454	0.0090	-0.0000
Proportion	0.380	0.259	0.129	0.107	0.094	0.031	0.001	-0.000
Cumulative	0.380	0.638	0.767	0.874	0.968	0.999	1.000	1.000
Variable	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**
Ca_meq	0.187	0.552	-0.237	-0.295	-0.132	0.694	-0.130	0.043
Mg_meq	0.028	0.612	-0.054	-0.182	-0.318	-0.681	-0.151	0.028
Na_meq	0.538	-0.193	0.098	0.188	0.002	-0.034	-0.742	0.277
K_meq	0.004	0.079	0.898	-0.419	0.078	0.078	-0.006	0.007
SO4_meq	0.449	0.239	-0.037	0.056	0.585	-0.132	0.440	0.428
HCO3_meq	-0.072	0.355	0.349	0.799	-0.248	0.167	0.121	0.068
Cl_meq	0.377	-0.305	0.017	-0.145	-0.686	0.016	0.427	0.300
TDScalc	0.571	0.028	0.043	0.083	0.018	-0.048	0.136	-0.802

Table 5-4
Summary of Domestic Wells Exceeding 1 mg/L Methane without Stable Isotope or Gas Composition Analyses
Garfield County Phase I Hydrogeological Characterization

Station ID	Sample Date	Sample ID	Type Well	UTM NAD 83X	UTM NAD 83Y	Analyte	Result	DETLIM	Units	Comment	Methane Origin
704332	1/28/2003	704332-012803-0	DOM	270247.97	4367082.2	Methane	36.7	0.05	mg/L	Wright Water Engineer Report - no isotope	UNK
703230	11/12/2004	703230-111204-0	DOM	270503	4373724.3	Methane	14	0.01	mg/L		UNK
704074	1/21/2003	704074-012103-0	DOM	272436.99	4367146.2	Methane	12.5	0.05	mg/L	8/02/02 = 0.3, 1/21/03 = 12.5 (WWE) 9/11/03 = <0.0008	UNK
703983	3/20/2003	703983-032003-0	DOM	272150.02	4374278.3	Methane	11	0.04	mg/l	3/20/03 = 11 (WWE) 4/13/05 = 3.9	UNK
704152	3/8/2005	704152-030805-0	DOM	273220.99	4366832.2	Methane	8.9	0.01	mg/L	8/2/02 - 1.4 mg/l 1/16/03 - 0.83 mg/l 3/8/05 - 8.9 mg/l	UNK
704050	3/11/2003	704050-031103-0	DOM	272326.02	4374184.3	Methane	8.04	0.04	mg/l	3/11/03 - 8.04 mg/l 4/30/04 - 1.4 mg/l 4/8/05 - 1.3 mg/l	UNK
704481	3/16/2005	704481-031605-0	DOM	274718.01	4367390.2	Methane	7.8	0.01	mg/L		UNK
703996	7/1/2003	703996-070103-0	DOM	272918.99	4367273.2	Methane	7.7	0.08	mg/l	8/20/02 - 1.2 mg/l 7/1/03 - 7.7 mg/l	UNK
703981	11/12/2002	703981-111202-0	DOM	274601.01	4368426.2	Methane	6.9	0.04	mg/l		UNK
704073	9/21/2004	704073-092104-0	DOM	268411.98	4375238.4	Methane	6	0.01	mg/L		UNK
704329	1/14/2003	704329-011403-0	DOM	271225.97	4366161.2	Methane	5.41	0.05	mg/L		UNK
704195	9/21/2004	704195-092104-0	DOM	272626.02	4374283.3	Methane	5.4	0.04	mg/L		UNK
704076	8/2/2002	704076-080202-0	DOM	272588.99	4367788.2	Methane	4.5	0.008	mg/l		UNK
704330	1/15/2003	704330-011503-WWE	DOM	272806.98	4365746.1	Methane	3.62	0.05	mg/L		UNK
704482	1/20/2005	704482-012005-0	DOM	274718.01	4367390.2	Methane	3.1	0.01	mg/L		UNK
703978	11/13/2002	703978-111302-0	DOM	274719.01	4367383.2	Methane	2.9	0.008	mg/l		UNK

Table 5-4
Summary of Domestic Wells Exceeding 1 mg/L Methane without Stable Isotope or Gas Composition Analyses
Garfield County Phase I Hydrogeological Characterization

Station ID	Sample Date	Sample ID	Type Well	UTM NAD 83X	UTM NAD 83Y	Analyte	Result	DETLIM	Units	Comment	Methane Origin
704068	9/21/2004	704068-092104-0	DOM	268542.98	4374814.3	Methane	2.7	0.01	mg/L	3/17/05 - 0.21mg/l 9/21/04 - 2.7 mg/l 6/13/03 - 1.6 mg/l 4/17/02 - 0.14 mg/l	UNK
704400	3/17/2005	704400-031705-0	DOM	271442.98	4366513.2	Methane	2.7	0.1	mg/L		UNK
704023	8/20/2002	704023-082002-0	DOM	272668.99	4367628.2	Methane	2.3	0.008	mg/l		UNK
703968	3/18/2003	703968-031803-0	DOM	271520.01	4374458.3	Methane	2.04	0.008	mg/l	3/18/04 - 2.04 mg/l 6/30/04 - ? 8/5/05 - 0.93 mg/l	UNK
703545	1/30/2003	703545-013003-0	DOM	271332.99	4369549.2	Methane	1.75	0.05	mg/L	WWE no isotope	UNK
704454	4/14/2005	704454-041405-0	DOM	272593.03	4374921.3	Methane	1.7	0.01	mg/L		UNK
703265	3/4/2002	703265-030402-0	WTR	273684.04	4374405.3	Methane	1.6	0.009	MG/L	COGCC no isotope	UNK
703942	2/25/2003	703942-022503-0	IRR	272088	4371068.2	Methane	1.6	0.008	mg/l	2/25/03 - 1.6, 9/11/03 - 1.5, 4/14/04 - 0.99, 5/5/04 - 0.036, 11/04/04 - 0.025, 11/1/05 - 0.0029	UNK
704500	4/14/2005	704500-041405-0	DOM	272784.03	4374572.3	Methane	1.6	0.01	mg/L		UNK
704050	4/30/2004	704050-043004-0	DOM	272326.02	4374184.3	Methane	1.4	-999	mg/L		UNK
704016	12/20/2002	704016-122002-WWE	DOM	270912.97	4365547.1	Methane	1.38	0.05	mg/L	12/20/02 - 1.38 mg/l (ACZ), 10/1/03 - 0.54 mg/l, 11/6/03 0.34 mg/l	UNK
703086	3/13/2003	703086-031303-0	DOM	271819.02	4374366.3	Methane	1.2	0.008	mg/l	7/12/97 - 0.006, 9/15/99 - 0.35, 3/13/03 - 1.2	UNK
703996	8/20/2002	703996-082002-0	DOM	272918.99	4367273.2	Methane	1.2	0.008	mg/l		UNK

Table 5-5
Summary of Methane Detections in 1997

Water Sample Source	Number of Sample Locations	Number of Sample Events	Number of Detections	Concentration Range (µg/L)	Sections with Methane >2 mg/L
Township 6S Range 92W					
Domestic Well	1	1	1	6.0	N/A
Township 7S Range 92W					
Domestic Well	4	4	1	9.0	N/A
Totals for 1997 by Water Source					
Domestic Well	5	5	2	6.0 - 9.0	N/A
Total for 1997	**5**	**5**	**2**	▨	▨

Table 5-6
Summary of Methane Detections in 1999

Water Sample Source	Number of Sample Locations	Number of Sample Events	Number of Detections	Concentration Range (mg/L)	Sections with Methane >2,000 µg/L
Township 6S Range 92W					
Domestic Well	1	1	1	0.450	N/A
Township 7S Range 92W					
Domestic Well	2	2	0	N/A	N/A
Township 7S Range 93W					
Domestic Well	1	1	0	N/A	N/A
Totals for 1999 by Water Source					
Domestic Well	4	4	1	N/A	N/A
Total for 1999	**4**	**4**	**1**	▨	▨

Table 5-7
Summary of Methane Detections in 2001

Water Sample Source	Number of Sample Locations	Number of Sample Events	Number of Detections	Concentration Range (mg/L)	Sections with Methane >2 mg/L
Township 6S Range 92W					
Domestic Well	6	10	9	0.0017 - 12	29, 33
Township 6S Range 93W					
Domestic Well	12	13	1	0.0014	N/A
Water Well	3	3	0	N/A	N/A
Township 7S Range 92W					
Domestic Well	2	2	0	N/A	N/A
Township 7S Range 93W					
Domestic Well	2	2	0	N/A	N/A
Totals for 2001 by Water Source					
Domestic Well	22	27	10	0.0014 - 12	29, 33
Water Well	3	3	0	N/A	N/A
Total for 2003	**25**	**30**	**10**	▨	▨

Table 5-8
Summary of Methane Detections in 2002

Water Sample Source	Number of Sample Locations	Number of Sample Events	Number of Detections	Concentration Range (mg/L)	Sections with Methane >2 mg/L
Township 6S Range 92W					
Domestic Well	12	12	4	0.016 – 1.9	N/A
Water Well	1	1	1	1.6	N/A
Spring	1	1	0	N/A	N/A
Township 6S Range 93W					
Domestic Well	4	4	1	6.8	19
Water Well	4	5	2	0.0018 – 0.0058	N/A
Township 7S Range 92W					
Domestic Well	26	27	14	0.0018 – 6.9	19, 23, 24
Water Well	4	4	2	0.0022 – 15	8
River	6	6	2	0.001 – 0.0017	N/A
Spring	3	3	1	0.0017	N/A
Township 7S Range 93W					
Domestic Well	8	8	0	N/A	N/A
Water Well	3	3	0	N/A	N/A
River	4	4	1	0.054	N/A
Spring	5	5	1	0.0011	N/A
Totals for 2002 by Water Source					
Domestic Wells	50	51	19	0.0018 – 6.9	23, 24
Water Wells	12	13	5	0.0018 – 15	8
River	10	10	3	0.001 – 54	N/A
Springs	9	9	2	0.0011 – 0.0017	N/A
Total for 2002	**81**	**83**	**29**		

Table 5-9
Methane Detections in 2003

Water Sample Source	Number of Sample Locations	Number of Sample Events	Number of Detections	Concentration Range (mg/L)	Sections with Methane >2 mg/L
Township 6S Range 92W					
Domestic Well	36	38	22	0.0015 - 11	29, 33, **34**
River	2	2	0	N/A	N/A
Spring	2	2	0	N/A	N/A
Township 6S Range 93W					
Domestic Well	9	9	1	0.0008	N/A
Township 7S Range 92W					
Domestic Well	39	47	24	0.0013 - 36.7	**23**, 26, 27, 28
Irrigation Well	3	4	3	0.0011 – 1.6	N/A
River	2	2	1	0.0095	N/A
Spring	7	8	2	0.0011 – 0.210	N/A
Pond	2	2	2	0.035 – 0.049	N/A
Township 7S Range 93W					
Domestic Well	6	7	2	0.0024 – 4.3	**26**
Spring	2	2	2	0.0057 – 0.013	N/A
Totals for 2003 by Water Source					
Domestic Wells	90	101	49	0.0008 - 36.7	**23**, 26, 27, 29, 33, 34
Irrigation Wells	3	4	3	0.0011 – 1.6	N/A
River	4	4	1	0.0095	N/A
Spring	11	12	4	0.0011 – 0.210	N/A
Ponds	1	2	2	30.05 – 0.049	N/A
Totals for 2003	**109**	**123**	**59**		

Table 5-10
Summary of Methane Detections in 2004

Water Sample Source	Number of Sample Locations	Number of Sample Events	Number of Detections	Concentration Range (mg/L)	Sections with Methane >2 mg/L
Township 6S Range 92W					
Domestic Well	23	28	20	0.0013 - 14	3, 29, **33**, 34
River	2	2	0	N/A	N/A
Spring	11	11	1	0.0013	N/A
Pond	2	2	0	N/A	N/A
Township 6S Range 93W					
Domestic Well	24	25	3	0.0012 – 0.0082	N/A
Water Well	1	1	0	N/A	N/A
Spring	2	2	0	N/A	N/A
Township 7S Range 92W					
Domestic Well	34	228	144	0.0008 - 28	2, **3**, 10, 13, **23**
Irrigation Well	3	29	17	0.0014 - 1.2	N/A
Monitoring well	26	129	106	0.0008 - 14	2, **12**
Air Sparging Well	5	20	19	0.001 - 16	**12**
River	12	263	262	0.0011 - 12	**12**
Creeks	1	1	1	0.0087	N/A
Spring	9	41	4	0.0032 - 0.440	N/A
Pond	11	41	37	0.0015 - 0.760	N/A
Township 7S Range 93W					
Domestic Well	10	10	0	N/A	N/A
Spring	3	4	1	0.010	N/A
Pond	1	1	0	N/A	N/A
Totals for 2004 by Water Source					
Domestic Well	91	291	167	0.0008 - 28	2, **3**, 10, 13, **23,** 29, 33, 34
Irrigation Well	3	29	17	0.0014 - 1.2	N/A
Water Well	1	1	0	N/A	N/A
Monitoring well	26	129	106	0.0008 14	2, **12**
Air Sparging Well	5	20	19	0.001 - 16	**12**
River	14	265	262	0.0011 - 12	**12**
Creeks	1	1	1	0.0087	N/A
Spring	25	58	6	0.0013 - 0.440	N/A
Pond	14	44	37	N/A	N/A
Total for 2004	**180**	**838**	**615**		

Table 5-11
Summary of Methane Detections in 2005

Water Sample Source	Number of Sample Locations	Number of Sample Events	Number of Detections	Concentration Range (mg/L)	Sections with Methane >2 mg/L
Township 6S Range 92W					
Domestic Well	55	69	32	0.0021 - 10	**27**, 33, 34
Water Well	1	1	0	N/A	N/A
River	2	2	0	N/A	N/A
Spring	12	20	0	N/A	N/A
Pond	6	6	2	0.015 - 0.053	N/A
Township 6S Range 93W					
Domestic Well	5	5	0	N/A	N/A
Water Well	1	1	0	N/A	N/A
Township 7S Range 92W					
Domestic Well	31	171	112	0.0008 - 20	2, **3,** 10, 13, 24, 26
Irrigation Well	3	17	14	0.0035 - 0.260	N/A
Monitoring well	27	209	180	0.0008 - 16	2, **12**
Air Sparging Well	15	36	25	0.0014 - 11	**12**
River	10	277	264	0.0008 - 0.290	N/A
Spring	4	25	0	N/A	N/A
Seep	1	1	1	11	**12**
Pond	5	26	26	0.0031 - 0.320	N/A
Township 7S Range 93W					
Domestic Well	6	6	0	N/A	N/A
Totals for 2005 by Water Source					
Domestic Well	97	251	144	0.0008 - 20	2, **3**, 10,13, 24,26, 27, 33, 34,
Irrigation Well	3	17	14	0.0035 - 0.260	N/A
Water Well	2	2	0	N/A	N/A
Monitoring well	27	209	180	0.0008 - 16	2, **12**
Air Sparging Well	15	36	25	0.0014 - 11	**12**
River	12	279	264	0.0008 - 0.290	N/A
Spring	16	45	0	N/A	N/A
Seep	1	1	1	11	**12**
Pond	11	32	28	0.0031 - 0.320	N/A
Total for 2005	**184**	**872**	**656**		

Table 5-12
Groundwater Descriptive Statistics and Comparisons with Water Quality Standards

Well-Type	Analyte	Number of Values	Number of Non-detects	Pct Detects	Mean Concen-tration	Standard Deviation	Units	MCL[a]	COGW[b]	COSW[c]	Pct Above MCL	Pct Above GW	Pct Above SW
Air Sparging Well	Conductivity	6	0	100	678	163.06072	umho/cm				0	0	0
Air Sparging Well	pH field measured	6	0	100	8.4	0.3226143	SU				0	0	0
Air Sparging Well	Total Dissolved Solids	1	0	100	8500		mg/L		400		0	100	0
Domestic Well	Alkalinity total as CaCO3	681	28	95.888399	366.75468	156.73721	mg/L				0	0	0
Domestic Well	Arsenic	39	6	84.615385	0.0048359	0.0157816	mg/L	0.05	0.05	0.05	0	0	0
Domestic Well	Barium	9	4	55.555556	0.0592778	0.0565841	mg/L	2	2	1	0	0	0
Domestic Well	Bicarbonate as CaCO3	168	28	83.333333	347.29762	203.67236	mg/L				0	0	0
Domestic Well	Boron	30	0	100	0.118	0.047007	mg/L		0.75		0	0	0
Domestic Well	Bromide	427	157	63.23185	0.9138642	1.3809841	mg/L				0	0	0
Domestic Well	Calcium	709	32	95.486601	59.924471	62.912574	mg/L				0	0	0
Domestic Well	Carbonate as CaCO3	180	159	11.666667	40.144944	120.46949	mg/L				0	0	0
Domestic Well	Chloride	802	29	96.38404	147.52571	316.60996	mg/L		250	250	0	13.09227	13.09227
Domestic Well	Conductivity	1057	29	97.256386	5764.6284	79879.937	umho/cm				0	0	0
Domestic Well	Fluoride	691	63	90.882779	1.8949493	1.6696639	mg/L	4	4	2	11.5774	11.57742	35.89001
Domestic Well	Hardness as CaCO3	2	0	100	384.5	27.577164	mg/L				0	0	0
Domestic Well	Iron	674	302	55.192878	0.960142	7.4252594	mg/L		0.3	0.3	0	28.04154	28.04154
Domestic Well	Magnesium	703	43	93.883357	28.169933	37.247698	mg/L				0	0	0
Domestic Well	Manganese	664	254	61.746988	0.1837206	1.5275463	mg/L		0.05	0.05	0	24.24699	24.24699
Domestic Well	Nitrate as N	683	183	73.206442	6.2981669	13.864748	mg/L	10	10	10	15.6662	15.66618	15.66618
Domestic Well	Nitrate/Nitrite as N	3	1	66.666667	1.7733333	2.5627004	mg/L	10	10	10	0	0	0
Domestic Well	Nitrite as N	650	605	6.9230769	0.4620462	1.4128058	mg/L	1	1	1	1.53846	1.538462	1.538462
Domestic Well	pH field measured	736	0	100	7.7911685	0.5286154	SU				0	0	0
Domestic Well	Potassium	710	30	95.774648	3.0401761	8.8316685	mg/L				0	0	0
Domestic Well	Salinity	8	0	100	9.415	5.8650222	mg/L				0	0	0
Domestic Well	Selenium	668	224	66.467066	0.0952039	1.5498316	mg/L	0.05	0.05	0.05	13.7725	13.77246	13.77246

Table 5-12
Groundwater Descriptive Statistics and Comparisons with Water Quality Standards

Well-Type	Analyte	Number of Values	Number of Non-detects	Pct Detects	Mean Concen-tration	Standard Deviation	Units	MCL[a]	COGW[b]	COSW[c]	Pct Above MCL	Pct Above GW	Pct Above SW
Domestic Well	Sodium	693	30	95.670996	310.50248	326.48736	mg/L				0	0	0
Domestic Well	Specific Conductance	16	0	100	1167.75	753.61445	umho/cm				0	0	0
Domestic Well	Sulfate	701	6	99.14408	353.76676	565.85114	mg/L		250	250	0	32.52496	32.52496
Domestic Well	Total Dissolved Solids	1288	29	97.748447	1080.3494	845.34804	mg/L		400		0	87.96584	0
Domestic Well	Total Suspended Solids	1	0	100	15.5		mg/L				0	0	0
Irrigation Well	Alkalinity total as CaCO3	46	4	91.304348	375.06522	211.29263	mg/L				0	0	0
Irrigation Well	Bicarbonate as CaCO3	8	4	50	197.5	254.04696	mg/L				0	0	0
Irrigation Well	Bromide	34	10	70.588235	1.1217647	1.6459058	mg/L				0	0	0
Irrigation Well	Calcium	41	4	90.243902	43.339024	32.17711	mg/L				0	0	0
Irrigation Well	Carbonate as CaCO3	8	8	0	2.5	0	mg/L				0	0	0
Irrigation Well	Chloride	54	4	92.592593	283.23648	386.19477	mg/L		250	250	0	22.22222	22.22222
Irrigation Well	Conductivity	94	4	95.744681	39388.872	362129.48	umho/cm				0	0	0
Irrigation Well	Fluoride	43	4	90.697674	2.1586047	1.5093322	mg/L	4	4	2	20.9302	20.93023	51.16279
Irrigation Well	Iron	39	14	64.102564	0.3698718	0.5971709	mg/L		0.3	0.3	0	28.20513	28.20513
Irrigation Well	Magnesium	41	4	90.243902	14.884146	22.435165	mg/L				0	0	0
Irrigation Well	Manganese	41	10	75.609756	0.028122	0.0670281	mg/L		0.05	0.05	0	7.317073	7.317073
Irrigation Well	Nitrate as N	41	4	90.243902	52.10878	54.503563	mg/L	10	10	10	65.8537	65.85366	65.85366
Irrigation Well	Nitrite as N	41	38	7.3170732	0.8932927	2.0414063	mg/L	1	1	1	0	0	0
Irrigation Well	pH field measured	60	0	100	7.8568333	0.4201835	SU				0	0	0
Irrigation Well	Potassium	41	4	90.243902	9.6429268	14.415026	mg/L				0	0	0
Irrigation Well	Selenium	43	5	88.372093	0.059493	0.0506033	mg/L	0.05	0.05	0.05	48.8372	48.83721	48.83721
Irrigation Well	Sodium	41	4	90.243902	387.55805	292.16441	mg/L				0	0	0
Irrigation Well	Sulfate	37	0	100	222.32973	200.18383	mg/L		250	250	0	45.94595	45.94595
Irrigation Well	Total Dissolved Solids	103	4	96.116505	1432	1053.2238	mg/L		400		0	96.1165	0

Table 5-12
Groundwater Descriptive Statistics and Comparisons with Water Quality Standards

Well-Type	Analyte	Number of Values	Number of Non-detects	Pct Detects	Mean Concen-tration	Standard Deviation	Units	MCL[a]	COGW[b]	COSW[c]	Pct Above MCL	Pct Above GW	Pct Above SW
Monitoring Well	Alkalinity total as CaCO3	201	0	100	462.79005	179.70929	mg/L				0	0	0
Monitoring Well	Bromide	238	50	78.991597	0.4769748	1.1294623	mg/L				0	0	0
Monitoring Well	Calcium	213	10	95.305164	100.69014	98.193637	mg/L				0	0	0
Monitoring Well	Chloride	239	10	95.8159	73.804979	221.93089	mg/L		250	250	0	3.76569	3.76569
Monitoring Well	Conductivity	433	0	100	1045.7223	926.3114	umho/cm				0	0	0
Monitoring Well	Fluoride	200	1	99.5	1.5491	1.3093284	mg/L	4	4	2	5	5	19
Monitoring Well	Iron	213	10	95.305164	24.023192	33.857509	mg/L		0.3	0.3	0	94.83568	94.83568
Monitoring Well	Magnesium	213	10	95.305164	28.09831	19.50735	mg/L				0	0	0
Monitoring Well	Manganese	213	10	95.305164	1.8065023	2.7710579	mg/L		0.05	0.05	0	92.01878	92.01878
Monitoring Well	Nitrate as N	239	219	8.3682008	0.2818828	1.0748643	mg/L	10	10	10	0.41841	0.41841	0.41841
Monitoring Well	Nitrite as N	239	234	2.0920502	0.3332845	1.2077083	mg/L	1	1	1	0	0	0
Monitoring Well	pH field measured	238	0	100	7.6926471	0.5300578	SU				0	0	0
Monitoring Well	Potassium	212	12	94.339623	5.6079245	5.5101371	mg/L				0	0	0
Monitoring Well	Selenium	212	125	41.037736	0.0082297	0.0147114	mg/L	0.05	0.05	0.05	2.35849	2.358491	2.358491
Monitoring Well	Sodium	213	11	94.835681	159.69977	169.41461	mg/L				0	0	0
Monitoring Well	Sulfate	229	22	90.393013	65.340437	146.04404	mg/L		250	250	0	4.803493	4.803493
Monitoring Well	Total Dissolved Solids	453	0	100	660.14128	340.57031	mg/L		400		0	91.83223	0

[a] MCL refers to the EPA drinking water MCL.

[b] COGW means Colorado basic groundwater quality standards for drinking water.

[c] COSW means Colorado basic surface water quality standards for drinking water.

Table 5-13
Summary of Constituents Exceeding Groundwater Standards

Constituent	Groundwater Standard (mg/L)	Percent of Samples Above the Standard
Domestic Wells		
Chloride	250	13
Fluoride	4	11
Iron	0.3	28
Manganese	0.05	24
Nitrate as N	10	15
Selenium	0.05	13
Total dissolved solids (TDS)	400	88
Irrigation Wells		
Chloride	250	22
Fluoride	4	21
Iron	0.3	28
Manganese	0.05	7
Nitrate as N	10	66
Selenium	0.05	49
Sulfate	250	46
Monitoring Wells		
Iron	0.3	95
Manganese	0.05	92
Selenium	0.05	2
Sulfate	250	5
Total dissolved solids	400	92

Table 5-14
SAR Values in Groundwater by Well-Type

Well-Type	Number of Wells	Mean SAR	Mean Conductivity umho/cm
Irrigation wells	3	19.4	2065
Monitoring Wells	27	5.4	1105
Domestic Wells	96	13.1	2223

Table 5-15
PCA Output Parameters for Surface Water Major Ions

Results for: SW Garfield.MTW
Principal Component Analysis
Eigenanalysis of the Correlation Matrix

Eigenvalue	4.2469	1.4432	0.9761	0.5647	0.5408	0.2116	0.0166	0.0000
Proportion	0.531	0.180	0.122	0.071	0.068	0.026	0.002	0.000
Cumulative	0.531	0.711	0.833	0.904	0.971	0.998	1.000	1.000
Variable	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**
Ca_meq	0.234	0.575	0.073	-0.098	0.692	-0.297	0.171	0.054
Mg_meq	0.369	-0.375	0.228	0.176	0.357	0.614	0.363	0.065
Na_meq	0.426	0.072	-0.311	-0.046	-0.450	-0.225	0.642	0.223
K_meq	0.229	-0.159	0.773	-0.466	-0.199	-0.259	-0.024	0.007
SO4_meq	0.422	0.041	-0.319	-0.461	0.006	0.279	-0.512	0.407
HCO3_meq	0.345	-0.438	-0.041	0.498	0.156	-0.531	-0.308	0.193
Cl_meq	0.223	0.549	0.347	0.528	-0.350	0.238	-0.218	0.151
TDScalc	0.478	0.044	-0.154	-0.022	-0.073	0.022	-0.147	-0.847

Table 5-16
Standards Comparisons and Descriptive Statistics for Surface Water Quality

Water	Analyte	Number of Values	Number of Nondetects	Pct Detects	Mean Concentration	Std Deviation	Units	MCL[a]	COGW[b]	COSW[c]	Pct Above MCL	Pct Above GW	Pct Above SW
Pond	Alkalinity total as CaCO3	52	5	90.38	344.28	174.64	mg/L				0.0	0.0	0.0
Pond	Arsenic	4	0	100.00	0.03	0.04	mg/L	0.05	0.05	0.05	25.0	25.0	25.0
Pond	Barium	4	0	100.00	0.31	0.41	mg/L	2	2	1	0.0	0.0	0.0
Pond	Bicarbonate as CaCO3	7	4	42.86	228.43	335.35	mg/L				0.0	0.0	0.0
Pond	Bromide	41	30	26.83	0.14	0.20	mg/L				0.0	0.0	0.0
Pond	Calcium	60	4	93.33	61.41	33.88	mg/L				0.0	0.0	0.0
Pond	Carbonate as CaCO3	10	9	10.00	3.79	4.08	mg/L				0.0	0.0	0.0
Pond	Chloride	75	5	93.33	14.48	30.12	mg/L		250	250	0.0	0.0	0.0
Pond	Conductivity	117	2	98.29	707.78	330.84	umho/cm				0.0	0.0	0.0
Pond	Fluoride	63	7	88.89	0.79	0.50	mg/L	4	4	2	0.0	0.0	1.6
Pond	Iron	56	9	83.93	1.07	3.17	mg/L		0.3	0.3	0.0	53.6	53.6
Pond	Magnesium	58	4	93.10	37.67	28.43	mg/L				0.0	0.0	0.0
Pond	Manganese	58	6	89.66	0.09	0.16	mg/L		0.05	0.05	0.0	53.4	53.4
Pond	Nitrate as N	62	32	48.39	0.56	0.63	mg/L	10	10	10	0.0	0.0	0.0
Pond	Nitrite as N	60	60	0.00	0.12	0.11	mg/L	1	1	1	0.0	0.0	0.0
Pond	pH field measured	73	0	100.00	8.21	0.59	SU				0.0	0.0	0.0
Pond	Potassium	61	4	93.44	5.52	10.12	mg/L				0.0	0.0	0.0
Pond	Selenium	55	33	40.00	0.01	0.01	mg/L	0.05	0.05	0.05	3.6	3.6	3.6
Pond	Sodium	61	3	95.08	87.04	124.67	mg/L				0.0	0.0	0.0
Pond	Sulfate	59	1	98.31	134.79	444.44	mg/L		250	250	0.0	6.8	6.8
Pond	Total Dissolved Solids	135	4	97.04	504.67	400.05	mg/L		400		0.0	46.7	0.0
Spring	Alkalinity total as CaCO3	83	3	96.39	436.74	154.98	mg/L				0.0	0.0	0.0
Spring	Arsenic	5	0	100.00	0.00	0.00	mg/L	0.05	0.05	0.05	0.0	0.0	0.0
Spring	Bicarbonate as CaCO3	17	3	82.35	381.50	213.49	mg/L				0.0	0.0	0.0

Table 5-16
Standards Comparisons and Descriptive Statistics for Surface Water Quality

Water	Analyte	Number of Values	Number of Nondetects	Pct Detects	Mean Concentration	Std Deviation	Units	MCL[a]	COGW[b]	COSW[c]	Pct Above MCL	Pct Above GW	Pct Above SW
Spring	Boron	5	0	100.00	0.09	0.02	mg/L		0.75		0.0	0.0	0.0
Spring	Bromide	57	44	22.81	0.28	0.23	mg/L				0.0	0.0	0.0
Spring	Calcium	97	3	96.91	68.84	29.19	mg/L				0.0	0.0	0.0
Spring	Carbonate as CaCO3	17	17	0.00	2.50	0.00	mg/L				0.0	0.0	0.0
Spring	Chloride	115	3	97.39	15.41	23.47	mg/L		250	250	0.0	0.0	0.0
Spring	Conductivity	167	3	98.20	7793.1	87129.9	umho/cm				0.0	0.0	0.0
Spring	Fluoride	98	9	90.82	0.86	0.90	mg/L	4	4	2	1.0	1.0	3.1
Spring	Iron	92	52	43.48	0.45	1.73	mg/L		0.3	0.3	0.0	19.6	19.6
Spring	Magnesium	97	3	96.91	55.44	35.91	mg/L				0.0	0.0	0.0
Spring	Manganese	95	46	51.58	0.09	0.50	mg/L		0.05	0.05	0.0	15.8	15.8
Spring	Nitrate as N	94	9	90.43	7.05	15.22	mg/L	10	10	10	11.7	11.7	11.7
Spring	Nitrite as N	93	91	2.15	0.08	0.06	mg/L	1	1	1	0.0	0.0	0.0
Spring	pH field measured	119	0	100.00	7.69	0.46	SU				0.0	0.0	0.0
Spring	Potassium	96	3	96.88	5.65	6.57	mg/L				0.0	0.0	0.0
Spring	Selenium	96	39	59.38	0.01	0.01	mg/L	0.05	0.05	0.05	0.0	0.0	0.0
Spring	Sodium	97	4	95.88	111.87	109.86	mg/L				0.0	0.0	0.0
Spring	Specific Conductance	5	0	100.00	921.40	262.14	umho/cm				0.0	0.0	0.0
Spring	Sulfate	95	0	100.00	138.66	163.14	mg/L		250	250	0.0	15.8	15.8
Spring	Total Dissolved Solids	211	3	98.58	683.50	326.17	mg/L		400		0.0	95.3	0.0
Stream	Alkalinity total as CaCO3	136	7	94.85	315.39	143.72	mg/L				0.0	0.0	0.0
Stream	Arsenic	2	0	100.00	0.00	0.00	mg/L	0.05	0.05	0.05	0.0	0.0	0.0
Stream	Bicarbonate as CaCO3	20	7	65.00	223.78	188.47	mg/L				0.0	0.0	0.0
Stream	Boron	2	0	100.00	0.19	0.18	mg/L		0.75		0.0	0.0	0.0
Stream	Bromide	123	34	72.36	0.14	0.21	mg/L				0.0	0.0	0.0
Stream	Calcium	136	7	94.85	71.68	102.54	mg/L				0.0	0.0	0.0

Table 5-16
Standards Comparisons and Descriptive Statistics for Surface Water Quality

Water	Analyte	Number of Values	Number of Nondetects	Pct Detects	Mean Concentration	Std Deviation	Units	MCL[a]	COGW[b]	COSW[c]	Pct Above MCL	Pct Above GW	Pct Above SW
Stream	Carbonate as CaCO3	18	17	5.56	3.27	3.28	mg/L				0.0	0.0	0.0
Stream	Chloride	225	7	96.89	12.77	42.17	mg/L		250	250	0.0	0.4	0.4
Stream	Conductivity	600	7	98.83	702.75	353.39	umho/cm				0.0	0.0	0.0
Stream	Fluoride	133	24	81.95	0.78	0.49	mg/L	4	4	2	0.0	0.0	3.0
Stream	Iron	134	16	88.06	2.46	6.63	mg/L		0.3	0.3	0.0	77.6	77.6
Stream	Magnesium	135	7	94.81	35.83	67.62	mg/L				0.0	0.0	0.0
Stream	Manganese	135	14	89.63	0.18	0.29	mg/L		0.05	0.05	0.0	64.4	64.4
Stream	Nitrate as N	153	93	39.22	0.32	0.44	mg/L	10	10	10	0.0	0.0	0.0
Stream	Nitrite as N	153	151	1.31	0.11	0.04	mg/L	1	1	1	0.0	0.0	0.0
Stream	pH field measured	490	0	100.00	8.62	3.63	SU				0.0	0.0	0.0
Stream	Potassium	136	7	94.85	4.81	7.37	mg/L				0.0	0.0	0.0
Stream	Selenium	133	58	56.39	0.01	0.02	mg/L	0.05	0.05	0.05	0.8	0.8	0.8
Stream	Sodium	135	11	91.85	86.80	78.88	mg/L				0.0	0.0	0.0
Stream	Sulfate	148	0	100.00	72.06	116.10	mg/L		250	250	0.0	2.7	2.7
Stream	Total Dissolved Solids	650	7	98.92	450.36	243.39	mg/L		400		0.0	53.4	0.0

[a] MCL refers to the EPA drinking water MCL.

[b] COGW means Colorado basic groundwater quality standards for drinking water.

[c] COSW means Colorado basic surface water quality standards for drinking water.

Table 5-17
Summary of Constituents Exceeding Groundwater Standards

Constituent	Surface Water Standard (mg/L)	Percent of Samples Above the Standard
Ponds		
Arsenic	0.05	25
Iron	0.3	54
Manganese	0.05	53
Selenium	0.05	4
Sulfate	250	7
Springs		
Fluoride	2	3
Iron	0.3	20
Manganese	0.05	16
Nitrate as N	10	12
Sulfate	250	16
Streams		
Chloride	250	0.4
Fluoride	2	3
Iron	0.3	78
Manganese	0.05	64
Selenium	0.05	0.8
Sulfate	250	3

6.1 RELATIONSHIP BETWEEN WATER QUALITY AND GEOLOGY

The best groundwater is water that has spent the least amount of time in the ground, and is most isolated from mixing with deeper formation water. Alluvial aquifers in the study area have higher yields (production) than Wasatch Formation wells, and are generally lower in TDS, sodium, and chloride, constituents that can degrade the taste and usability of the water.

As freshwater from precipitation infiltrates below the ground surface and becomes groundwater in the Wasatch, sodium in the rock exchanges with calcium and magnesium in the water and the water becomes enriched with sodium. Bicarbonate is the dominant anion in this shallow water. Sulfate and chloride concentrations are also lower in these younger waters. Therefore, the best drinking water is found close to recharge areas, which are generally the more elevated areas within the study area. As groundwater moves from the higher areas down to lower areas, it evolves and picks up sodium and chloride ions, and potentially other metals (e.g., selenium, fluoride). However, the depth to water is usually greater in these higher regions (100+ feet on Grass Mesa).

Deeper formation water is considered the water present below the potable water in the Wasatch Formation (at least 600 feet deep). This includes the deeper Wasatch Formation, Mesaverde rocks present above the top of gas, and reservoir rocks in the underlying Mesaverde Group beneath the study area. This water is more evolved and has higher sodium and chloride concentrations, resulting in higher TDS values than shallow groundwater in the Wasatch. The deeper formation water is also under high pressure within the formation due to the hydrocarbon overpressure at depth in the basin. This water has the potential to flow upward toward the ground surface if sufficient interconnected fracture pathways are present. It is apparent that a groundwater source of sulfate is present in the Dry Hollow Gulch area. This sulfate source may be located at intermediate depths between the Wasatch potable water horizon and the deeper Mesaverde Group.

Locations where the thickness of the Wasatch Formation is greatest are most insulated from the movement of deeper formation water (Mesaverde group Formations) up toward the ground surface. Grass Mesa is located on about 6,000 feet of Wasatch Formation. The southeast portion of the study area is located on about 1,200 feet of Wasatch Formation, which provides less of a barrier to upward flow of deeper formation groundwater. However, if there are few fractures present in the Wasatch, 1,200 feet of predominately mudstone should provide an excellent seal. The overburden pressures are also likely higher in areas where the Wasatch Formation is thickest, which would increase the lithostatic pressure and reduce fracture apertures at depth.

It appears that water quality is also better in areas where the underlying Wasatch bedrock is composed predominately of mudstone (Grass Mesa area), with few laterally continuous sandstone units (Dry Hollow area). The mudstone may be less likely to fracture than sandstone from deeper-seated structural displacements. Fractures in mudstone may also anneal more readily than fractures in sandstone, creating fewer potential vertical conduits for deeper formation waters to move upward and mix with shallow groundwater.

Areas located the farthest from significant linear features are also less likely to have significant fracture zones present, which would minimize the potential for upward flow of deeper formation water and mixing with shallow groundwater.

6.2 LOCATIONS OF PRISTINE, IMPACTED, AND POTENTIALLY VULNERABLE WATER RESOURCES

Based upon the available data reviewed for this study, regions of the study area where groundwater and surface water resources are anticipated to be most pristine include the south, southwest, and west regions, including Grass and Flatiron Mesas. These areas are located at higher elevations, the Wasatch Formation is thicker, there is apparently less structural deformation (greatest distance from the Divide Creek anticline), and except for Grass Mesa, there have been relatively few gas wells completed to date.

Impacted regions are defined here as locations where groundwater and/or surface water quality is diminished by the presence of an organic (i.e. methane) or inorganic (i.e. fluoride) constituent above drinking water or agricultural use standards, or the taste or odor is significantly diminished to limit the usability of the water resource. A number of water wells in the eastern portion of the study area are impacted from elevated concentrations of dissolved methane, fluoride, selenium, and TDS. This area is generally east of Mamm Creek and west of Divide Creek. The northern quarter of this area, east of Dry Hollow, has fewer water wells with elevated concentrations of dissolved methane, fluoride, and TDS at this time, based on our review of existing data. The causes of the impacts to groundwater are unknown for most of this area. However, water wells in this area are located above the Divide Creek anticline, which is a region of deep-seated structural displacement during more recent geologic time, and has resulted in the formation of subsurface fracture zones. These fracture zones may serve as natural pathways for fluids and gas to migrate upwards and mix with shallower groundwater and surface water. The thickness of the Wasatch Formation is also thinner

In some portions of this eastern area, groundwater quality has reportedly been impacted due to gas well drilling and completion activities; specifically, operations associated with the Schwartz 2-15B well and the G33 pad. Less certain are the cause of impacts to groundwater in the southeast corner of the study area. One explanation that groundwater in this area has been impacted by releases of fluids and potentially thermogenic gas from poor plugging and abandonment procedures at several old (pre-1990) well locations. Additional investigation of specific gas well locations in this area, and resampling and analysis of water wells to evaluate the nature of the methane (biogenic versus thermogenic), is necessary to be more certain of the degree and extent of potential impacts in this region.

Groundwater in the area near Section 3 T7S R92W and Section 34 T6S 92W is impacted by elevated concentrations of fluoride, selenium, sulfate, TDS, and dissolved methane (biogenic or thermogenic). Biogenic methane could be caused by conditions localized around the water well, or be generated from within the Wasatch Formation in this area. The elevated selenium, fluoride, and sulfate occurrences in this area could also be caused by lithologic conditions in this interval of the Wasatch Formation. The geology in this area likely created the occurrence more densely spaced fractures. The area is located on the top of the plunging nose of the Divide Creek anticline, which likely adds to the structural deformation. The presence of a thicker Molina-like sandstone unit in this area may accentuate the formation of fracture zones. Based on the problems encountered while cementing the Schwartz 2-15B well, the presence of subsurface fractures complicates drilling and completion operations and requires more diligence to ensure sufficient integrity of the completion. Although impacts to shallow groundwater have occurred in this general area from gas well operations, this area is apparently sufficiently fractured to create a more dynamic groundwater flow zone and potentially allow mixing of deeper fluids with shallow groundwater and surface water.

The areas where water well specific capacity is highest may be directly related to the number and interconnectivity of subsurface fractures. Unfortunately, these areas are likely more prone to also serve as migration pathways for deeper formation water and potentially hydrocarbons to migrate upward toward the ground surface.

Unidentified areas that have the potential to be impacted by oil and gas operations include the Hunter Mesa region located near the center of the study area. The area has been extensively developed with gas wells and there are very few groundwater wells in the area. Therefore, there is only limited water quality data to evaluate for a relatively large area (roughly 8 square miles).

This section outlines the types of activities that could be performed as part of a Phase II program. Recommendations are categorized in several areas and were in part developed to address data gaps identified while conducting the Phase I characterization.

Additional Data Evaluation in Areas of Concern

Focused data evaluation of individual gas wells in areas of elevated methane concentrations or for wells with uncertain completion integrity. Detailed review of gas well data (completion reports, cement bond logs, sundry notices) stored in COGCC on-line database for all identified wells in the study area that are:

- plugged and abandoned wells
- wells with surface casing lengths less than 600 feet
- wells with bradenhead pressures greater than 150 psi for more than 6 months
- wells requiring remedial cementing
- wells completed prior to 1984
- wells located within 2,000 feet hydraulically upgradient of any water well where methane concentrations exceed 2 mg/L, fluoride exceeds 4 mg/L, or the groundwater is a sodium-chloride type.

Field Investigation

Focused investigation utilizing soil gas readings in the area around specific wells identified as potential or likely problem wells based on the “Additional Data Evaluation” described above

General field investigation using vehicle-mounted gas detection instruments to identify potential gas seeps in the Hunter Mesa area, and other regions where ground water monitoring data is limited. This survey would be conducted in areas with few gas wells and areas with densely spaced gas wells.

Develop a long term groundwater and surface water sample collection program. Collect baseline data in areas not already drilled (stay ahead of the drilling).

If not already completed, develop a sampling and analysis plan that addresses collection, analysis, and quality assurance and quality control specifications for groundwater and surface water sampling for major cations and anions, organics, metals, stable isotopes, and gases. Specify the water quality parameters to be measured in the field. Identify any specific chemical constituents used in drilling and completion operations and include these on the analyte list.

Prior to visiting the site to collect a water well sample, the contractor should review the SEO database and determine the well permit number and review the appropriate well completion report. The current well owner should be interviewed to assist in determining the history of the water well ownership, construction, and permitting.

When on-site at the wellhead, the contractor should confirm that the water well matches the well permit description (casing diameter and total depth), survey the location with a handheld GPS unit (more accurate equipment may be appropriate), make a sketch map of the sample location referencing local landmarks with the date shown and scan this as an electronic attachment with the sample data.

The County may consider if it is appropriate to sample all domestic water wells within the study area on a two-year frequency (i.e. sample one-half of the domestic water wells, or approximately 225 wells every year) to provide a water quality database to allow evaluation of spatial and temporal changes, or consistency, in water quality. The sampling method will follow approved procedures. Analyze water samples for dissolved methane and major cations and anions, fluoride, selenium, and bromide. Submit laboratory results to respective homeowners and the Garfield County environmental engineer or public health administrator. Laboratory results sent to homeowners should be accompanied by a cover letter describing the water quality standards and health affects for individual analytes, as appropriate.

Confirm whether stable isotope and gas composition data exist for all water wells where dissolved methane concentrations exceed 2 mg/L. Resample all water wells where methane exceeds 2 mg/L and data is unavailable for stable isotope, gas composition, and major cations and anions.

Sample water wells located near the Philpott gas well, the Questar Fairview #1 gas well, and the Koch Mobil well. Conduct gas seep analyses around these wells.

Locate all existing water wells and surface water locations in the Hunter Mesa area and evaluate if additional water quality samples should be collected and analyzed.

Collect samples of produced water from additional wells located throughout the study area. Characterize the water quality of the produced water.

Conduct a minimum 72-hour pump test on 3 water wells located along a higher specific capacity trend in an area overlying lineaments, and also on 3 lower specific capacity water wells not related to major specific study area lineaments. These wells would be chosen based on similar well completion histories and at comparable depths. Results would be used to determine if Wasatch water wells along or adjacent to lineaments have higher specific capacities with respect to wells not located near or along basement lineaments. This data would be used to confirm the specific capacity estimates from the pump installation tests.

Modifications and Improvements to Existing Data Collection and Data Entry Processes

Garfield County may want to evaluate if they need to undertake discussions with the State Engineers Office and current water well drilling contractors in the area to improve and standardize several aspects of water well drilling, reporting, and data input of well completion information. This could include:

- Standardization of geologic logging procedures, water level measurement, pump testing, and documentation of exact well location performed by water well drillers
- Training of water well drillers to use the new procedures
- Use of inexpensive handheld GPS units by water well drillers to survey in well locations
- Certification of water well drillers to operate within Garfield County
- Teaming with the State Engineers Office to oversee water well driller filing of well completion and well testing paperwork

Garfield County may want to evaluate if they need to undertake discussions with the COGCC regarding operators reporting additional drilling and completion data for wells completed within the county. This could include:

- Reporting of mud weights used while drilling to document subsurface pressure conditions. This could consist of a mud log, a pressure chart, or reporting of mud weight at a minimum of 3 depths in each well, including the Wasatch and total drilled depth.
- Reporting of intervals where gas was observed coming into the hole, depths where loss of well control occurred, and/or a job summary report
- Completion of a shut-in pressure test at the initial well on each pad
- Timing and accuracy of operator report submittal to COGCC. Include bottom hole location coordinates, cement intervals, cement bond log

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Appendix A

GPS Waypoint Data for Measured Sections

Appendix A
GPS Waypoint Data for Measured Sections

Handheld GPS waypoints for outcrop measured sections in the Phase I Hydrogeologic Characterization Study, NAD83

latd	latm	lats	latitude	longd	longm	longs	longitude	elev	date	time	comment	location
39	30	32	39.50888889	-107	44	19	-107.7386111	5670	10/18/2005	22:38:23	Measured section waypoint	SEC101
39	30	32	39.50888889	-107	44	19	-107.7386111	5670	9/23/2005	20:43:12	Measured section waypoint	SEC101
39	30	33	39.50916667	-107	44	21	-107.7391667	5735	10/18/2005	22:38:23	Measured section waypoint	SEC102
39	30	33	39.50916667	-107	44	21	-107.7391667	5735	9/23/2005	20:43:12	Measured section waypoint	SEC102
39	30	35	39.50972222	-107	44	22	-107.7394444	5769	10/18/2005	22:38:23	Measured section waypoint	SEC103
39	30	35	39.50972222	-107	44	22	-107.7394444	5769	9/23/2005	20:43:12	Measured section waypoint	SEC103
39	30	33	39.50916667	-107	44	25	-107.7402778	5783	10/18/2005	22:38:23	Measured section waypoint	SEC104
39	30	33	39.50916667	-107	44	25	-107.7402778	5783	9/23/2005	20:43:12	Measured section waypoint	SEC104
39	30	50	39.51388889	-107	44	43	-107.7452778	5876	10/18/2005	22:38:23	Measured section waypoint	SEC105
39	30	50	39.51388889	-107	44	43	-107.7452778	5876	9/23/2005	20:43:13	Measured section waypoint	SEC105
39	30	48	39.51333333	-107	44	48	-107.7466667	5977	10/18/2005	22:38:23	Measured section waypoint	SEC106
39	30	48	39.51333333	-107	44	48	-107.7466667	5977	9/23/2005	20:43:13	Measured section waypoint	SEC106
39	30	46	39.51277778	-107	44	49	-107.7469444	6047	10/18/2005	22:38:23	Measured section waypoint	SEC107
39	30	46	39.51277778	-107	44	49	-107.7469444	6047	9/23/2005	20:43:13	Measured section waypoint	SEC107
39	27	52	39.46444444	-107	37	19	-107.6219444	6014	10/18/2005	22:38:23	Measured section waypoint	SEC302
39	27	52	39.46444444	-107	37	19	-107.6219444	6014	9/23/2005	20:43:13	Measured section waypoint	SEC302
39	27	52	39.46444444	-107	37	24	-107.6233333	6073	10/18/2005	22:38:23	Measured section waypoint	SEC303
39	27	52	39.46444444	-107	37	24	-107.6233333	6073	9/23/2005	20:43:13	Measured section waypoint	SEC303
39	27	53	39.46472222	-107	37	27	-107.6241667	6193	10/18/2005	22:38:23	Measured section waypoint	SEC304
39	27	53	39.46472222	-107	37	27	-107.6241667	6193	9/23/2005	20:43:13	Measured section waypoint	SEC304
39	27	54	39.465	-107	37	28	-107.6244444	6325	10/18/2005	22:38:24	Measured section waypoint	SEC305
39	27	54	39.465	-107	37	28	-107.6244444	6325	9/23/2005	20:43:13	Measured section waypoint	SEC305
39	27	50	39.46388889	-107	37	37	-107.6269444	6348	10/18/2005	22:38:24	Measured section waypoint	SEC306
39	27	50	39.46388889	-107	37	37	-107.6269444	6348	9/23/2005	20:43:13	Measured section waypoint	SEC306
39	27	46	39.46277778	-107	37	43	-107.6286111	6428	10/18/2005	22:38:24	Measured section waypoint	SEC307
39	27	46	39.46277778	-107	37	43	-107.6286111	6428	9/23/2005	20:43:13	Measured section waypoint	SEC307
39	27	44	39.46222222	-107	37	45	-107.6291667	6417	10/18/2005	22:38:24	Measured section waypoint	SEC308
39	27	44	39.46222222	-107	37	45	-107.6291667	6417	9/23/2005	20:43:13	Measured section waypoint	SEC308
39	27	43	39.46194444	-107	37	45	-107.6291667	6424	10/18/2005	22:38:24	Measured section waypoint	SEC309
39	27	43	39.46194444	-107	37	45	-107.6291667	6424	9/23/2005	20:43:13	Measured section waypoint	SEC309
39	27	43	39.46194444	-107	37	46	-107.6294444	6424	10/18/2005	22:38:24	Measured section waypoint	SEC310
39	27	43	39.46194444	-107	37	46	-107.6294444	6424	9/23/2005	20:43:14	Measured section waypoint	SEC310
39	27	42	39.46166667	-107	37	47	-107.6297222	6453	10/18/2005	22:38:24	Measured section waypoint	SEC311
39	27	42	39.46166667	-107	37	47	-107.6297222	6453	9/23/2005	20:43:14	Measured section waypoint	SEC311
39	27	41	39.46138889	-107	37	49	-107.6302778	6479	10/18/2005	22:38:24	Measured section waypoint	SEC312
39	27	41	39.46138889	-107	37	49	-107.6302778	6479	9/23/2005	20:43:14	Measured section waypoint	SEC312
39	27	41	39.46138889	-107	37	49	-107.6302778	6502	10/18/2005	22:38:24	Measured section waypoint	SEC313TOP
39	27	41	39.46138889	-107	37	49	-107.6302778	6502	9/23/2005	20:43:14	Measured section waypoint	SEC313TOP
39	27	53	39.46472222	-107	37	21	-107.6225	6045	10/18/2005	22:38:24	Measured section waypoint	SEC3FENCE
39	27	53	39.46472222	-107	37	21	-107.6225	6045	9/23/2005	20:43:14	Measured section waypoint	SEC3FENCE
39	25	29	39.42472222	-107	43	23	-107.7230556	6869	10/18/2005	22:38:25	Measured section waypoint	SEC401
39	25	29	39.42472222	-107	43	23	-107.7230556	6869	9/23/2005	20:43:14	Measured section waypoint	SEC401
39	25	32	39.42555556	-107	43	25	-107.7236111	6953	10/18/2005	22:38:25	Measured section waypoint	SEC402
39	25	32	39.42555556	-107	43	25	-107.7236111	6953	9/23/2005	20:43:14	Measured section waypoint	SEC402
39	25	33	39.42583333	-107	43	26	-107.7238889	7010	10/18/2005	22:38:25	Measured section waypoint	SEC403
39	25	33	39.42583333	-107	43	26	-107.7238889	7010	9/23/2005	20:43:14	Measured section waypoint	SEC403
39	25	35	39.42638889	-107	43	30	-107.725	7116	10/18/2005	22:38:25	Measured section waypoint	SEC404
39	25	35	39.42638889	-107	43	30	-107.725	7116	9/23/2005	20:43:14	Measured section waypoint	SEC404
39	25	34	39.42611111	-107	43	34	-107.7261111	7169	10/18/2005	22:38:25	Measured section waypoint	SEC405
39	25	34	39.42611111	-107	43	34	-107.7261111	7169	9/23/2005	20:43:14	Measured section waypoint	SEC405
39	25	31	39.42527778	-107	43	38	-107.7272222	7218	10/18/2005	22:38:25	Measured section waypoint	SEC406
39	25	31	39.42527778	-107	43	38	-107.7272222	7218	9/23/2005	20:43:15	Measured section waypoint	SEC406
39	25	30	39.425	-107	43	39	-107.7275	7214	10/18/2005	22:38:25	Measured section waypoint	SEC407
39	25	30	39.425	-107	43	39	-107.7275	7214	9/23/2005	20:43:15	Measured section waypoint	SEC407
39	25	27	39.42416667	-107	43	41	-107.7280556	7279	10/18/2005	22:38:25	Measured section waypoint	SEC408
39	25	27	39.42416667	-107	43	41	-107.7280556	7279	9/23/2005	20:43:15	Measured section waypoint	SEC408
39	25	23	39.42305556	-107	43	36	-107.7266667	6983	10/18/2005	22:38:25	Photo Waypoint	SEC4PANO
39	25	23	39.42305556	-107	43	36	-107.7266667	6983	9/23/2005	20:43:15	Photo Waypoint	SEC4PANO
39	25	26	39.42388889	-107	43	40	-107.7277778	7150	10/18/2005	22:38:25	Photo Waypoint	SEC4PHOTO
39	25	26	39.42388889	-107	43	40	-107.7277778	7150	9/23/2005	20:43:15	Photo Waypoint	SEC4PHOTO
39	25	27	39.42416667	-107	43	21	-107.7225	6832	9/24/2005	16:54:51	Measured section waypoint	SEC4ROUTE
39	29	40	39.49444444	-107	38	28	-107.6411111	5855	10/18/2005	22:38:25	Measured section waypoint	SEC501
39	29	41	39.49472222	-107	38	31	-107.6419444	5925	10/18/2005	22:38:26	Measured section waypoint	SEC502
39	29	45	39.49583333	-107	38	33	-107.6425	5920	10/18/2005	22:38:26	Measured section waypoint	SEC503
39	29	46	39.49611111	-107	38	32	-107.6422222	5973	10/18/2005	22:38:26	Measured section waypoint	SEC504
39	29	48	39.49666667	-107	38	32	-107.6422222	6036	10/18/2005	22:38:26	Measured section waypoint	SEC505
39	29	49	39.49694444	-107	38	31	-107.6419444	6111	10/18/2005	22:38:26	Measured section waypoint	SEC506
39	32	49	39.54694444	-107	37	27	-107.6241667	5305	10/18/2005	22:38:26	Measured section waypoint	SECDAVIS1
39	32	49	39.54694444	-107	37	27	-107.6241667	5305	9/23/2005	20:43:15	Measured section waypoint	SECDAVIS1
39	32	53	39.54805556	-107	37	33	-107.6258333	5664	10/18/2005	22:38:26	Measured section waypoint	SECDAVIS2
39	32	53	39.54805556	-107	37	33	-107.6258333	5664	9/23/2005	20:43:15	Measured section waypoint	SECDAVIS2
39	32	53	39.54805556	-107	37	35	-107.6263889	5742	10/18/2005	22:38:26	Measured section waypoint	SECDAVIS3
39	32	53	39.54805556	-107	37	35	-107.6263889	5742	9/23/2005	20:43:15	Measured section waypoint	SECDAVIS3