Oil & Natural Gas Technology

DOE Award No.: DE-AD26-06NT02045

Final Report

Anticipated and Observed Impacts to Groundwater Associated with the Construction Use of Infiltration Impoundments in the Powder River Basin

Submitted by:
Arthur Langhus Layne-LLC
dba ALL Consulting
1718 South Cheyenne Avenue
Tulsa, Oklahoma 74119

Prepared for:
United States Department of Energy
National Energy Technology Laboratory

Office of Fossil Energy

ACKNOWLEDGEMENTS

This study was conducted as a combined effort by ALL Consulting (ALL), the Wyoming Department of Environmental Quality (WDEQ), and the Montana Board of Oil and Gas Conservation (MBOGC). The researchers would like to thank the following for their cooperation and assistance with the various aspects of this project: Marathon Oil Corporation for access to their data for the impoundments along the Powder River; The Termo Company, J.M. Huber, Fidelity Exploration and Production Company, and Yates Petroleum for access to the impoundment sites studied in this investigation; Industry, Federal and State Agency employees who provided a review and comments on the project; Jim Sams with the DOE Pittsburgh group, Andrew Bobst with the BLM in Miles City, Montana, Mike McKinley with the BLM in Buffalo, Wyoming; and especially the landowners within Wyoming who allowed the researchers access to their land during the field investigation.

DISCLAIMER

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

The use of surface impoundments for managing produced water from Coal Bed Natural Gas (CBNG) development has become a popular choice for many operators in the Powder River Basin of Wyoming and Montana, in the past 20 years of CBNG. Impoundments allow the rancher to use the water for livestock and crops also, some of the water will infiltrate into the subsurface and may reach the groundwater system. According to Wyoming State Engineer's office estimates from 2004, as many as 2,000 impoundments were being utilized for CBNG produced water management in the Wyoming portion of the PRB alone, current estimates are up to 4,000 impoundments are being utilized. The impacts of these impoundments on surface water and groundwater are unknown. These unknowns have given cause for alarm, as environmental groups and private citizens are expressing concerns that impoundments may have negative impacts to water resources. Recent research indicates that negative impacts predicted to result from impoundments have been over generalized. The research performed in under this project indicates that impacts to groundwater from impoundments appear to be determined primarily by site specific factors. In some settings negative impacts have been observed, while in other settings the impacts have been negligible or positive.

This project was a multi-phase investigation into the use and operation of infiltration systems for the management of coal bed natural gas produced water within the Powder River Basin. The focus of the project was identifying regional and local geologic, geochemical and hydrogeologic characteristics of the PRB and how those characteristics restrain or augment impoundments. The project included the gathering and evaluation of site specific and regional data within the PRB related to the use and operation of impoundments. In particular, this research evaluated the anticipated and observed impacts from the use of impoundments. This summary report is intended to aid an operator or regulatory agency in identifying the anticipated impacts to local soils, groundwater, and surface water from the use of impoundments.

The following criteria that have the potential to affect resultant groundwater quality as the CBNG produced water infiltrates through soil and bedrock, and mixes with the shallow groundwater: nature of the site (on-channel vs. off-channel, distance to outcrop, infiltration rates, stratigraphy, and type and abundance of soluble minerals), produced water quality and quantity, depth and quality of the underlying groundwater, and distance to surface water. From these criteria, six issues were identified as potential impacts:

- Dissolution of Minerals and Changes to the Quality of Infiltrating Water
- Mineralization of the Soil
- Mixing with Shallow Groundwater
- Change of Infiltration Rate
- Direction of Water Flow

EXTRANEOUS ISSUES

In addition to this document, three other documents were developed under this project to address issues associated with the management of CBNG produced water, each of which is summarized in this document. The first document addressed the issue of re-injection of CBNG produced water in the PRB. Re-injection or the lack of a requirement of re-injection by regulators has been used as a discussion point by Non-Governmental Organizations when commenting on the practices of the CBNG industry. The summaries presented in this document address the technical aspects associated with potential for re-injection and injection of CBNG produced water to be successful in the PRB. The second paper summarized addresses the issue of water statistics related to the PRB and CBNG produced water. A great deal of emphasis is placed upon the volumes of water that are produced over the lifetime of a CBNG producing well. This paper relates water statistics from everyday life to CBNG produced water volumes in an attempt to give an everyday perspective to some of the water statistics that are commonly addressed relative to CBNG development in the PRB. The final document summarized in this report addresses the siting, design, construction, and reclamation of CBNG impoundments. This document's intent is to provide a variety of best management practice type discussions regarding impoundments constructed in association with CBNG development in the PRB.

In 2006, ALL Consulting and the Wyoming Department of Environmental Quality conducted a field investigation to evaluate the impacts under impoundments which have been undergoing the infiltration of CBNG produced water. A summary of the investigation methods and activities including a discussion of the findings of the shallow subsurface geology are included in this document. The shallow subsurface geology was determined early on in the study to be the primary controlling factor for the impacts which occur under these impoundments so the discussion of the shallow geology is extensive in this report.

Finally, this report includes a discussion and analysis of observed impacts to groundwater that were obtained from the field investigation and from outside data sources. The discussion focuses on detailing data from the first groundwater zone encountered below the impoundments at alluvial and non-alluvial aquifers. The research presented documents the lack of adverse impacts that occurred under these impoundments that have been raised at several other sites (including the Skewed and Juniper Draw sites) and the adverse impacts that Non-Governmental Organizations have claimed will affect groundwater resources. In the case of the sites located near the Powder River alluvium, shallow groundwater quality typically improved, while those sites located over non-alluvial aquifers showed little to no change in most instances.

THIS PAGE INTENTIONALLY LEFT BLANK

ACRONYMS

amsl	above mean sea level
bls	below land surface
btc	below top of casing
bgs	below ground surface
BMP	Best Management Practice
BLM	Bureau of Land Management
CEC	Cation Exchange Capacity
DOE	Department of Energy
DPT	direct push technology
CBNG	coal bed natural gas
EIS	Environmental Impact Statement
HSA	Hollow-Stem Auger
MOU	Memorandum of Understanding
MBOGC	Montana Board of Oil and Gas Conservation
NPS	non-point source
PRB	Powder River Basin
PVC	polyvinyl chloride
QAPP	Quality Assurance Project Plan
RFD	Reasonable Foreseeable Development
SDWA	Safe Drinking Water Act
SAR	Sodium Adsorption Ratio
SOP	Standard Operating Procedures
SWL	Static water level
TDS	Total Dissolved Solids
USGS	U. S. Geological Survey
UIC	Underground Injection Control
USDW	underground source of drinking water
USCS	Unified Soil Classification System
WMP	Water Management Plan
WDEQ	Wyoming Department of Environmental Quality
WSEO	Wyoming State Engineer’s Office

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

Anticipated and Observed Impacts to Groundwater Associated with the Construction and Use of Infiltration Impoundments in the Powder River Basin

The following is the final report on the Research Project DE-AD26-06NT0245 Coal Bed Natural Gas Research performed by ALL Consulting for the United States Department of Energy (DOE). The research contained several phases that were released separately during the project. The first three sections of this final report explain the rationale behind the research, presents the theory on potential impacts which provided the basis for the research and summarizes the various earlier reports related to the study of infiltration systems and the much larger issue of environmentally responsible water management for the Coal Bed Natural Gas industry. The second portion of the final report describes in detail the investigation of groundwater impacts adjacent to infiltration impoundments used for coal bed natural gas water. Both portions of this report are intended to provide a better understanding of and provide direction for the management of coal bed natural gas produced water.

This project was a multi-phase investigation into the use and operation of infiltration systems for the management of coal bed natural gas (CBNG) produced water across the Powder River Basin (PRB). The research focused on the regional and local geologic, geochemical and hydrogeologic characteristics of the PRB and the degree to which those characteristics restrain or augment infiltration as a management option for the handling of CBNG produced water. The project included the gathering and evaluation of site specific and regional data within the PRB related to the use and operation of infiltration systems. In particular the later portions of this report look into anticipated and observed impacts associated with the long term use of infiltration systems and are intended to aid an operator or regulatory agency in identifying the anticipated impacts to local soils, groundwater, and surface water from the use of infiltration systems.

CBNG is a clean-burning fuel that can be used for a multitude of purposes. Today CBNG supplies nearly 9% of the nation’s natural gas supplies. Almost 2% (1.20 BCF/day) of the U.S. total natural gas supply comes from CBNG from the Powder River Basin of Wyoming and Montana. The production of natural gas from CBNG resources in the western U.S. including the PRB has become a critical component of the national energy supply. If production of natural gas from these sources were lost, the economies of Wyoming and Montana would be impacted and the nation’s energy supply could be affected. Changes to environmental regulations are being considered in both states that could have substantial effects on the CBNG industry and potentially result in reduced production of CBNG resources. One of the principal considerations for the changes of environmental regulations relative to CBNG in these states is concern about whether water produced from CBNG wells can be managed in an environmentally responsible manner.

When CBNG is produced, copious volumes of formation water are also brought to the surface; currently in excess of 1.8 million barrels per day or 75 million gallons per day across the PRB. This large volume of water is seen by some residents as a boon to ranching for a variety of reasons, including an ongoing drought, while other residents feel this water is a threat to the land. Furthermore, government agencies are forced to evaluate the new challenges associated with this rapidly growing industry. Federal and state regulators to date have found CBNG produced water to be the roadblock to CBNG development because of its variability; rates of production typically start out high and then decline, and water quality varies from field-to-field, coal seam-to-coal seam and well-to-well. As such, these variations place a burden on regulators and CNBG operators to manage CBNG water within a regulatory environment that is forced to vary in reaction to new issues which seem to continually arise; the variability represents a challenge to CBNG operators and regulators alike. One of the most commonly used management options for CBNG produced water is the use of infiltration systems (impoundments which are unlined and allow water to infiltrate through the bottom into the subsurface).

Off-Channel Impoundment from the LX Bar Creek Watershed, Wyoming

OVERVIEW OF THE RESEARCH PROJECT

This three-year research effort was undertaken at the request of the DOE to answer questions about the management of produced water from coal bed natural gas. One of the goals of this research is to assess whether or not infiltration systems provide a means to environmentally manage CBNG produced water.

An infiltration system is an impoundment, or pit, constructed on the land surface that CBNG operators are using to managing CBNG produced water. Currently impoundments are being used across much of the Powder River Basin of Wyoming and are expected to be used as CBNG development expands into the Montana portion of the PRB. An impoundment can be constructed by building a dam; or embankment, in an existing drainage flow path so as to restrict the flow of surface water and thus allowing the water to pool behind the dam, this type of system is commonly referred to as an on-channel impoundment. An impoundment can also be constructed by excavating a pit outside of an existing drainage path, typically on a low flat area relative to the surrounding terrain. Additional capacity is established by utilizing the excavated material to build up the embankment around the excavated area; this type of system is commonly referred to as an off-channel impoundment. A more detailed description of on and off channel infiltration systems, and the benefits and limitations of utilizing each, can be found in the summary of the *Siting, Design, Construction and Reclamation Guidebook for Coalbed Natural Gas Impoundments* (ALL, 2006) in Section 3 of this document.

This research project represents an approach toward cooperative investigation into the management of CBNG produced water and groundwater resource management enrolling three federal agencies (Bureau of Land Management, U.S. Geological Survey, DOE), four state agencies from two states (Wyoming Oil and Gas Conservation Commission, Wyoming Department of Environmental Quality, Wyoming State Engineer’s Office, and Montana Board of Oil and Gas Conservation), and several industry players working together to characterize the groundwater beneath an array of on-channel and off-channel impoundments. The research was planned from the outset to maximize value to the funding agency (DOE) as well as produce data of the greatest accuracy and reproducibility. Quality Assurance was planned to secure appropriately reliable data that would support the analyses and conclusions of the project. Monitoring wells, geological samples, groundwater samples, wire-line well-logs, and lab analyses of groundwater were handled in accordance with a detailed Quality Assurance Plan. To that end, the researchers used a variety of data acquisition tools to approach the question whether or not groundwater impacts are widespread under impoundments in the PRB.

The use of surface impoundments as a practice for managing water produced from CBNG development has become a popular choice for many operators in the Powder River Basin. One of primary reasons for the use of impoundments in the area is the large rainfall deficit this area experiences. Figure 1-1 and Figure 1-2 present the annual inches of rainfall and evaporation for the PRB. The two figures show that some areas experience up to 40 inches of rainfall deficit (evaporation is 40 inches greater than rainfall annually). The Wyoming State Engineer's Office (WSEO) estimated in 2004 that were more than 2,000 of these impoundments in operation in the Wyoming portion of the PRB. The impact from these impoundments is widely unknown, and this has given cause for concern to many environmental groups claiming that the impoundments will ultimately have negative impacts on groundwater and surface water resources. Research performed to date and the limited monitoring data collected to date have indicated that the impacts to shallow groundwater appear to be site specific, and evidence of significant negative impacts to surface water has not been realized. However, there are still many unknowns regarding the extent and nature of the chemical changes that may occur in the subsurface as result of CBNG produced water infiltrating through the surficial deposits of the PRB. Because of these considerable unknowns and the potential for CBNG development in Wyoming and Montana to continue, the Wyoming Department of Environmental Quality (WDEQ), the Montana Board of Oil and Gas Conservation (MBOGC), and ALL Consulting conducted this research effort.

Evaluation of the impacts to groundwater under CBNG impoundments in the PRB started with research projects conducted by the Bureau of Land Management (BLM) (Buffalo, Wyoming office) and the U.S. Geological Survey (USGS). The study focused on an intense investigation of an off-channel impoundment (Skewed Reservoir) constructed south of Buffalo, Wyoming. Early on in the investigation the researchers discovered that infiltrating produced water from the impoundment (Total Dissolved Solids (TDS) of ~2,500 mg/L) was interacting with the shallow weathered bedrock and soils to produce water with TDS concentrations greater than 110,000 mg/L approximately 22 feet below land surface (bls) and as high as 29,000 mg/L at 50 feet bls (Mike McKinley personal communication, 2004). When the preliminary results of the study were presented in 2004 by the BLM, the results raised concern from regulatory agencies and non-governmental organizations because of the relative short time (~6 months) for these changes to occur. Additionally, these changes appeared to show TDS would continue to increase with depth in the shallow subsurface indicating that this could be a continuing condition until bedrock was reached at 50 feet bls. The potential for these changes in infiltrating water quality to be widespread across the PRB caused concern among industry and regulators relative to the future uses of CBNG impoundments for water management in the PRB. The results presented from the Skewed Reservoir site led other researchers to investigate impoundments across the PRB and in part guided the direction of this study to determine if these large scale alterations to infiltrating water chemistry are prevalent across the PRB, or are the magnitude of impacts observed at the Skewed Reservoir a result of particular site specific conditions.

Figure 1-1: Precipitation in the PRB

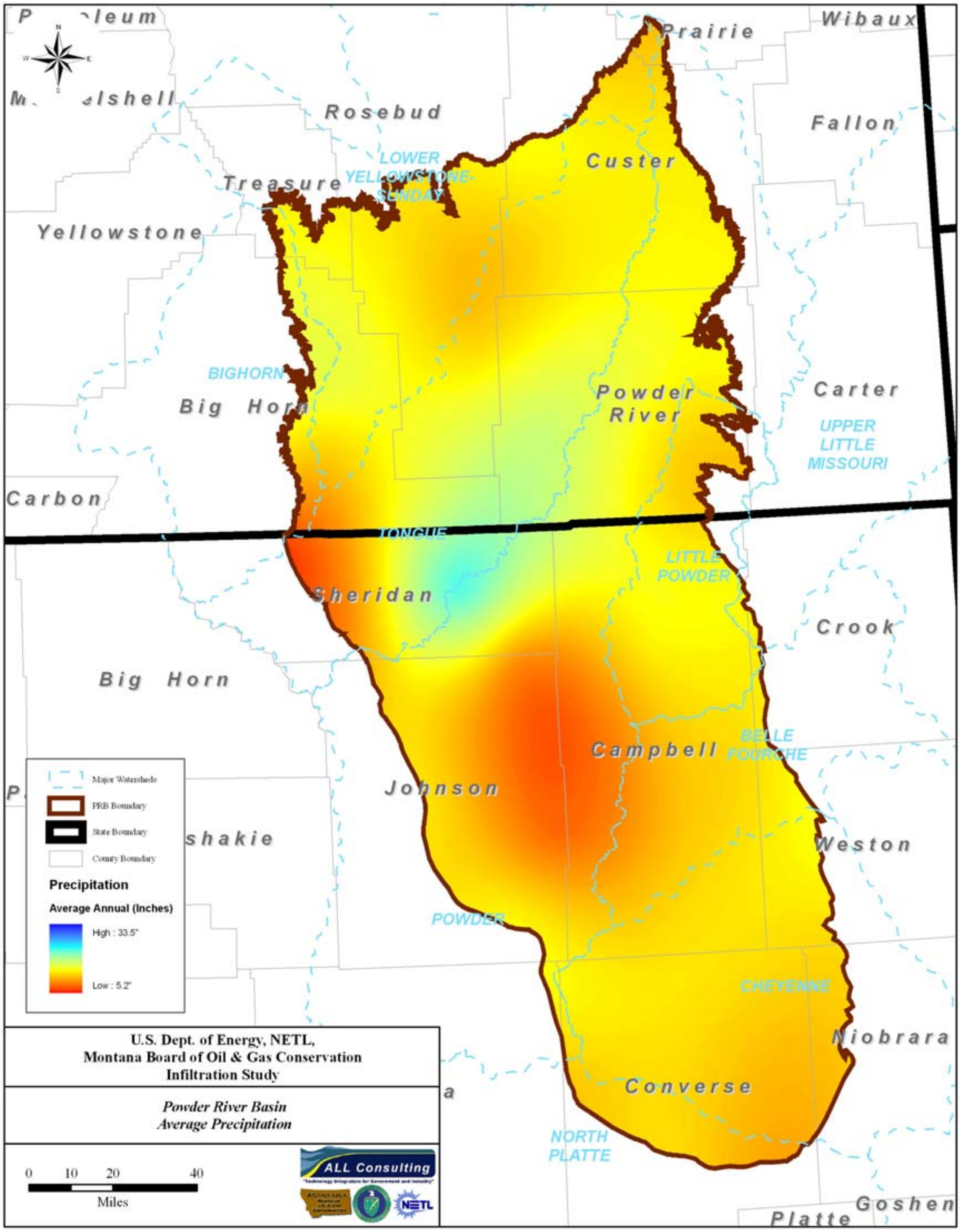
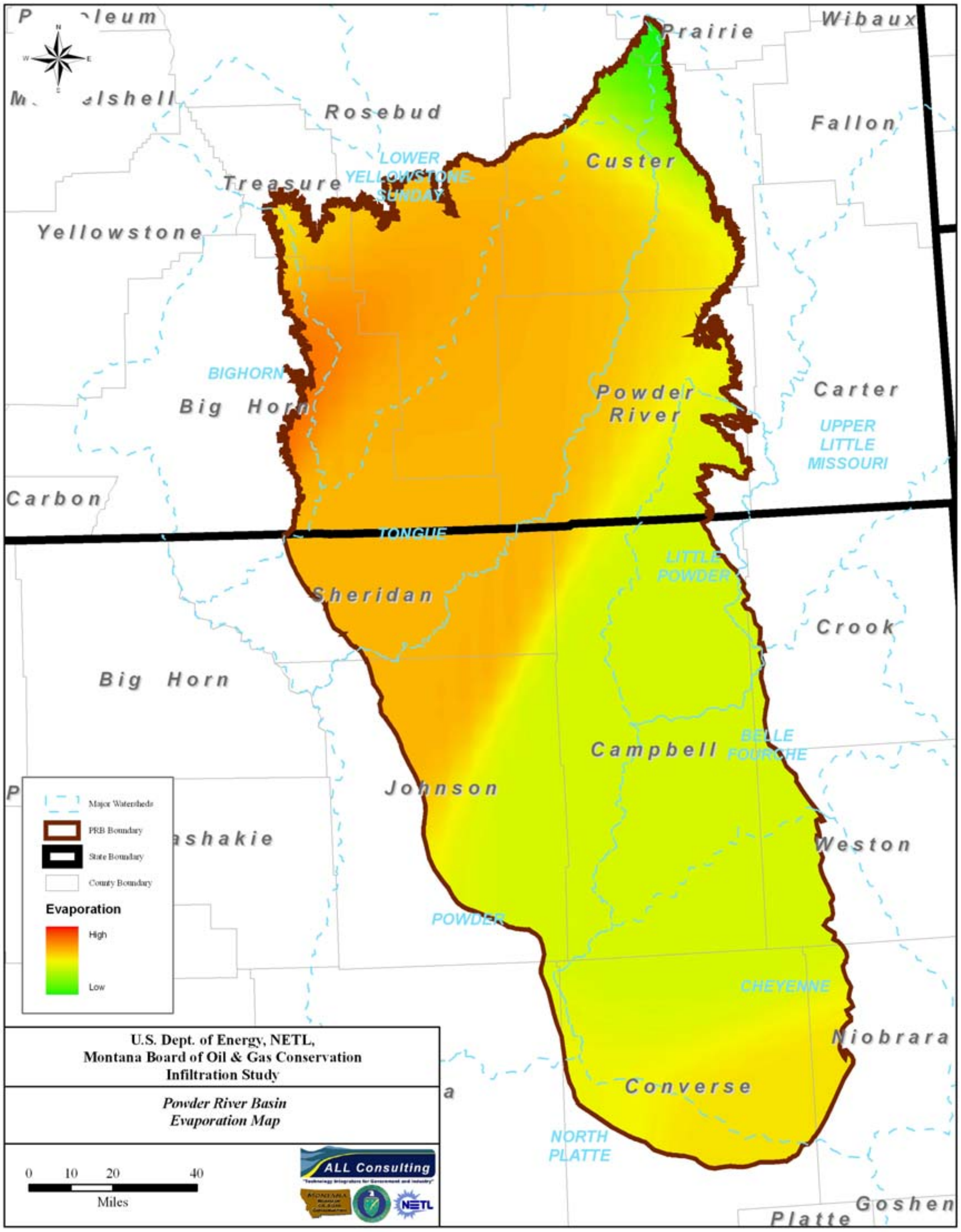


Figure 1-2: Evaporation in PRB



The MBOGC which has the responsibility of permitting and overseeing the use of infiltration ponds when they are built in the Montana portion of the PRB is also interested in determining the effects these impoundments might have on environmental resources. CBNG development has begun to expand in Montana during the last two years, and when the BLM finishes its Supplement Environmental Impact Statement on CBNG development on federal lands and minerals in the Powder River Basin of Montana, that development is expected to increase rapidly in the coming years. ALL Consulting, in partnership with the MBOGC, has been contracted by the DOE to research infiltration systems as these systems are used with CBNG development, in order to identify the impacts from the use of infiltration systems for produced water management, identify a means to improve the design, construction and use of these infiltration systems, and to assist in collecting data for other DOE funded research related to CBNG impoundments in the PRB.

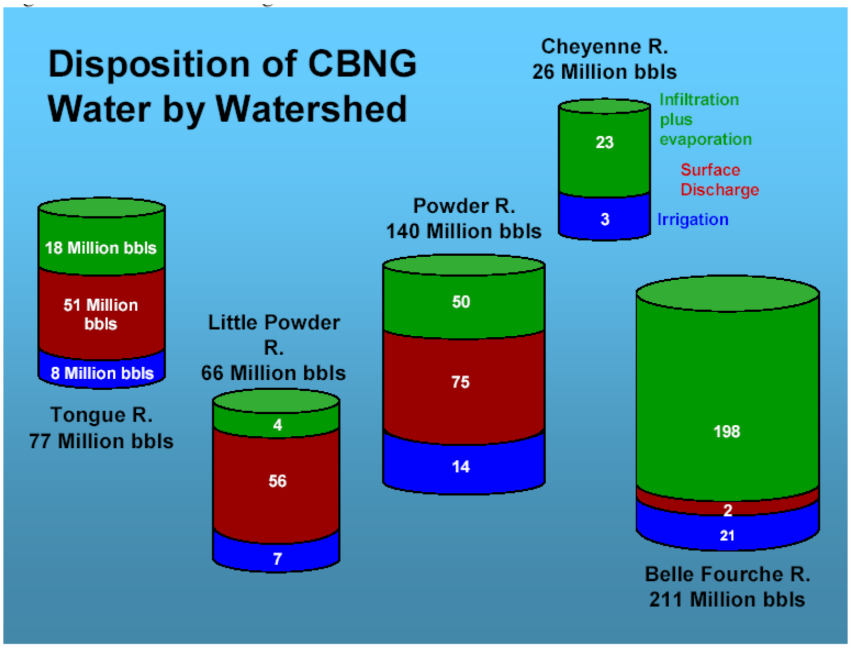
The WDEQ and ALL Consulting had each initiated infiltration/impoundment related research projects in 2004. Both organizations met early during their research projects to discuss the goals of each group. During the meeting it was determined that a cooperative effort to collect information on shallow groundwater quality and vadose zone materials near CBNG infiltration impoundments would benefit both parties. As a result the WDEQ and ALL Consulting entered into a Memorandum of Understanding (MOU) for the purpose of collecting data relative to the effects of infiltrating CBNG produced water from impoundments within the Wyoming portion of the PRB. Additionally, the WDEQ allowed ALL Consulting to review impoundment monitoring documents submitted by CBNG operators with production in Wyoming. This cooperative effort was the first of its kind with regard to CBNG produced water quality data and allowed for both an expansion of the research effort and a more detailed review of existing regulatory data than was ever possible before this research effort was undertaken.

INTRODUCTION TO CBNG WATER MANAGEMENT

The management of produced water often represents the greatest economic variable in the profitability of a CBNG field. Operators must manage this water at low costs, protect the local environment, and be consistent with traditional activities such as ranching, farming, and wildlife support. Conventional oil and gas production often involves re-injection of produced water into the hydrocarbon reservoir, but this is not prudent with CBNG reservoirs. The geological conditions in the PRB make the subsurface disposal (i.e. injection) of produced water very difficult and expensive. Non-conventional facilities can emplace CBNG water into subsurface zones much like injection devises. Impoundments can be fitted with boreholes through the floor of the pit into bedrock zones beneath. Subsurface drip irrigation can increase infiltration rates many-fold. Infiltration impoundments and these technologies challenge existing regulatory classifications.

Federal land managers request that operators have sufficient capacity to manage expected volumes of CBNG water prior to development. Operators will have to manage a range of water volumes throughout the history of each development. Several options for water management are used in the PRB by CBNG operators under varying conditions (ALL, 2004). These options each have their costs and benefits, but infiltration impoundments have historically been the most frequently used. Typical costs include actual price of construction, costs of permitting and monitoring the pond, and potential liabilities due to possible environmental effects. These costs will influence the economic viability of a new CBNG project; if costs are too high or are largely unknown, the CBNG project could be abandoned. Water management costs exert a great deal of control on the economics of a CBNG project.

Figure 1-3: Impoundments, CBNG Water Management by Watershed in the PRB as of 2006



CBNG in the PRB represents an important economic sector for the energy industry; CBNG production in November 2007 was occurring at the rate of 1,170 MMcf/day for the Wyoming portion and 30 MMcf/day for the Montana portion. At an average price of $3/mcf, this represents a total of $1.3 Billion/year split between the operator, mineral owner, county taxes, state taxes, and federal taxes. Income to the operator is of course partly spent on employee salaries and contractor fees. CBNG production is an important facet of today's business climate in the PRB. In order for this economic engine to continue running, CBNG operators have to be able to manage produced water. Water must be managed in an environmentally safe and an economically reasonable manner. Today an estimated 55% of the basin's produced CBNG water is managed by storage in impoundments (ALL, 2005) and if that management option were to go away due to public and regulator reservations concerning impoundments, 55% of CBNG production (660

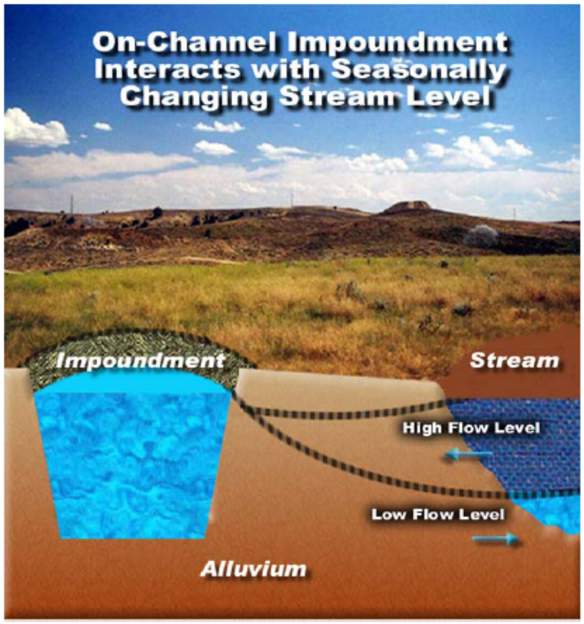
MMcf/day) would require alternative management options or these wells could be shut-in. If these wells were to be shut-in, this would represent a loss to Wyoming and Montana economies of an estimated $715 Million/year.

An important part of the BLM's Plan of Development, required of every CBNG project involving Federal minerals, is the Water Management Plan (WMP) as detailed in the Siting, Design, and Construction Report (ALL, 2006). A WMP is highly site-specific and incorporates the drilling plan for the project including numbers of wells, forecast production characteristics of each well, and timing of each well. The drilling/development plan will be used to calculate the water production schedule for the project; it is this schedule that will determine the management options to be used in conjunction with the CBNG project. Some water may be treated and discharged to streams while some may be used for managed irrigation; the projected rates of water management under each option over time will form the Water Budget (Figure 1-3).

INTRODUCTION TO INFILTRATION IMPOUNDMENTS

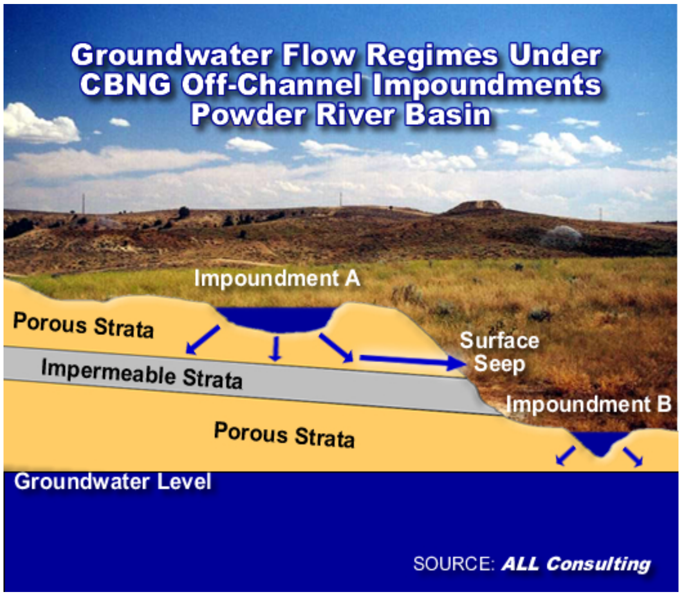
In the 20 years of CBNG activity in the PRB, produced water has often been managed by the use of large impoundments that store the water, allow the rancher to use the water for his livestock and crops, allow part of it to evaporate, and allow part of it to infiltrate into the subsurface. Several types of infiltration impoundments can be used in connection with CBNG water, and all of these impoundments are closely regulated with appropriate siting, construction, and operating limits (ALL, 2006). Impoundments can be constructed within the alluvium of active streams as on-channel pits (Figure 1-4). CBNG water in on-channel pits has the potential to interact with alluvial groundwater with the possibility of communicating with the stream itself, as shown in the schematic. Impoundments can also be constructed above alluvium on bedrock isolated from drainage into streams as off-channel impoundments (Figure 1-5). Some impoundments will infiltrate water at a high rate while others will have a low rate of infiltration. At question is whether some impoundments can, or have caused impacts to native groundwater.

Figure 1-4: Schematic Diagram of On-Channel Impoundment



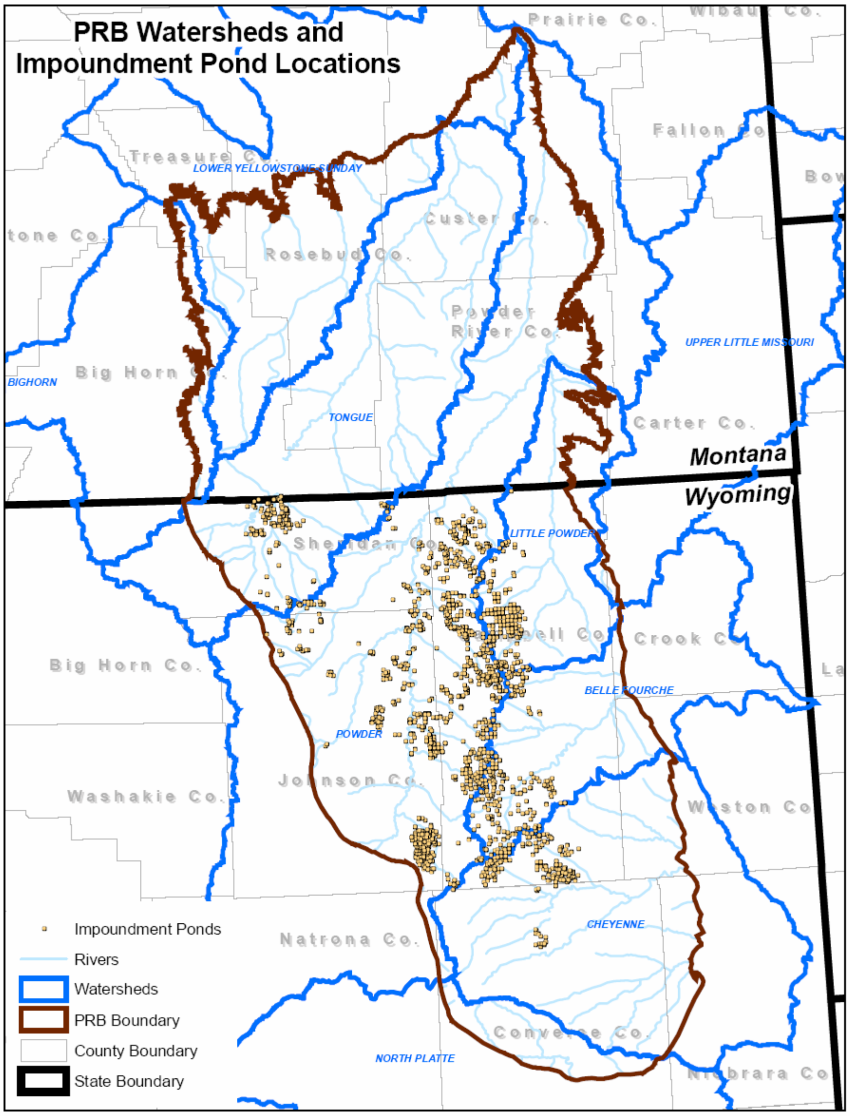
In excess of 2,000 impoundments are being used by CBNG operators in the PRB (Figure 1-6). While the majority of these structures have functioned without problems, some particular impoundments have been singled out as environmental problems that have impacted surface water and groundwater. Some of the impoundments have exhibited leaks under the dam and have been associated with salt water impacts to a deep, fresh water aquifer. Among those, the Skewed Impoundment has been used as a prime example. Infiltrating CBNG water appears to have increased in TDS content as it infiltrated the subsoil and bedrock. The infiltrating water apparently impacted a high quality water aquifer located nearly 100 feet below the impoundment when high-TDS water infiltrated and mixed with the groundwater. These have caused operators to be wary of their use, have made private citizens view the impoundments with suspicion, and made regulators cautious in approving their use.

Figure 1-5: Schematic Diagram of Off-Channel Impoundment



Impoundments are usually constructed close to the location of CBNG production to reduce the cost associated with the transportation of produced water. Therefore, operators often look for sites located close to their production facilities to site and construct an impoundment, as can be seen in Figure 1-6. The locations of the impoundments in Figure 1-6 illustrate the regions of the PRB which have experienced the greatest level of CBNG development.

Figure 1-6: Permitted CBNG Impoundments in the PRB.



PURPOSE AND OBJECTIVES

The purpose of this paper is to provide a summary of the overall work that was completed as a part of this project. This project included several phases of investigation into CBNG produced water management as it relates to the PRB with a particular focus on determining if the severe chemical alterations to infiltrating water identified in early impoundment research projects occur at other impoundments in the PRB. The purpose of this project also included evaluating potential conditions within the environment that would aid in the prediction of impacts CBNG produced water infiltration impoundments would have on the local soils, groundwater and surface water. In addition, this paper defines the results of a series of field investigations at impoundments within the PRB that were conducted in 2006.

The objectives of this report are to summarize the various earlier reports related to the study of infiltration systems and the much larger issue of environmentally safe water management for the CBNG industry that was researched by ALL Consulting. The first objective of this report is to provide a summary of previous research on re-injection and injection practices, water statistics in the PRB, and siting, design and construction of impoundments. The second objective is to provide the summary of the research into groundwater adjacent-to and down-gradient from CBNG infiltration impoundments in the PRB. In determining which sites to investigate for the field portion of this project, the researchers evaluated the geology and hydrogeology of the prospective sites and combined that information with the chemical constituents that would be analyzed to determine the final assessment techniques to be used and which locations were to be sampled. The presentation of a summary of these decisions is also an objective of this project.

The CBNG impoundment investigation strategy was derived from discussions among the project team members and the available monitoring program information that had been collected by CBNG operators and submitted to the WDEQ. These discussions and available data sets allowed the project team to focus on a set of primary considerations necessary for the completion of the field component of this research. These considerations included:

- ***Geological Considerations:*** The surficial geology of the PRB is highly varied with the Tertiary Wasatch and Fort Union formations outcropping across the basin. These formations are the product of the accumulation of sediments from various depositional progressions which have resulted in a thick stratigraphic sequence of inter-bedded coals, sands, silts, and clays. These formations have subsequently been dissected by major rivers and their tributaries which have resulted in the deposition of alluvial deposits within and adjacent to current channels. The variable surficial geology was one of the primary considerations when developing the plans for this study. Because of the many natural variations which may exist in the surficial and near surface geology, field personnel were relied upon to make interpretive decisions in the field relative to the location of borings, wells, and groundwater measurements.

- ***Hydrogeologic Considerations:*** Depth to groundwater was expected to vary from one impoundment to the next based on local differences in topography and geology. Although shallow unconfined aquifers were present in some areas, the varied geology present in the PRB resulted in groundwater being encountered at different depths at nearly each of the impoundments studied.

  As shallow unconfined groundwater generally flows from topographic highs toward the creeks and tributaries of the major rivers, it was assumed during the drilling process that topographic highs represented hydrologic highs. By establishing a minimum of two monitoring wells at each impoundment, one in the assumed up-gradient position and one down-gradient of the impoundment, the background groundwater quality was identified for all of the impoundments. Generally this proved to hold true during this investigation, however in some instances first groundwater was not encountered in an unconfined groundwater system and therefore groundwater gradient did not reflect surface topography.

- ***Constituents of Concern Considerations:*** The goal of the groundwater sampling activities was to collect groundwater samples that were indicative of the existing groundwater conditions, with the hope of determining both natural and impacted groundwater quality. Shallow groundwater water quality in the PRB varies widely as evidenced from recent monitoring data submitted to the WDEQ. These data indicate that Total Dissolved Solids can vary from under 1,000 mg/L to more than 15,000 mg/L across the area. Field measurements of electrical conductivity were taken during drilling / completion operations but such data was found to be unsuitable in assessing differences between background groundwater quality and infiltrated groundwater quality. It was also determined by the research team that some of the constituents being collected and analyzed for during this investigation could be affected by the sampling protocol utilized. This included metals constituents which are generally affected by the pH of groundwater as well as the level of turbidity in the wellbore. In order to minimize induced influences on the quality of groundwater samples taken, well development and purging activities which utilized low stress protocols were implemented by the research team. This adaptation of stringent sampling protocols including the institution of standard operating procedures utilized during field operations provides a high level of confidence to the data collected and the resultant analysis.

SCOPE OF THE PROJECT

Activities included within the scope of the project were: researching available construction and monitoring data on existing infiltration systems; coordinating data acquisition and research efforts with governing agencies; incorporating data from other research projects and industry contacts; and researching site specific and regional soil, groundwater, and surface water data within the PRB. Existing impoundment details were also researched to identify local conditions as well as design and construction parameters. Prior to initial analysis, the research included the development of variables for analysis which were based on data from available impoundments. Variables included such considerations as: water quantity and quality; on-channel vs. off-channel impoundments; geology and mineralization; depth to groundwater; distance to surface water; and other characteristics. Research into site-specific and regional conditions was used to define methodologies that can be employed to quantify changes and impacts to the existing environment that results from the utilization of infiltration systems.

On-Channel Impoundment in the PRB Wyoming

Infiltration System Theory and Analytical Criteria for the Identification of Potential Impacts

INTRODUCTION

In order to effectively assess the potential changes to soils, groundwater, and surface water from an infiltration system, a variety of site-specific analytical criteria must be considered to develop a valid theoretical model of potential impacts. The forecasted impacts may affect where an operator chooses to construct an infiltration impoundment. It is important to consider each individual criterion with scrutiny, as the collective whole of the criteria can either validate or invalidate the model when compared to actual field observations.

The following have been identified as the primary analytical criteria that control resultant water quality as the water infiltrates, dissolves salts along the flow path, and mixes with shallow groundwater: nature of infiltration system location (on-channel vs. off-channel, infiltration rates and geology/mineralization variations), produced water quality and quantity, depth and quality of the underlying groundwater, and distance to surface water. This section discusses each of the criterions individually, in terms of how each can be included in the development of an analytical and theoretical model.

This section also discusses infiltration systems in terms of a theoretical assessment of initial impacts and attempts to identify what could be expected to occur as CBNG produced water infiltrates through the soils/bedrocks within the PRB from an infiltration pond during an extended period of time. Six corollary issues have been identified as the focus of this theoretical discussion:

1. **Dissolution of Minerals and Changes to the Quality of the Infiltrating Water:** Infiltrating water may dissolve minerals that are present in the soils and bedrock if the water is under-saturated with respect to the constituents present in the soils and bedrock and if the geochemical reaction is not kinetically, stoichiometrically, or time limited.
2. **Mineralization of the Soil:** Infiltrating water may lose constituents to the precipitation of minerals into the soil if the infiltrating water is at super saturation with respect to the constituents of that mineral as long as the geochemical reactions are not kinetically, stoichiometrically, or time limited.
3. **Mixing with Shallow Groundwater:** The mixing of infiltrating water with existing groundwater may result in a change to the chemistry of the resultant groundwater, which may or may not result in changes to the conditions of items 1 or 2 above. Such mixing may improve, degrade, or have

no appreciable impact on the quality of the groundwater depending upon the initial water quality, conditions 1 and 2, the quality of the existing groundwater, and the volume of groundwater moving through the affected area.

4. **Change of Infiltration Rate:** The precipitation of minerals (salts, sulfates or carbonates) and the dispersion of clay minerals present in the soils beneath the infiltration system may result in a decreasing rate of infiltration over time and, thus, effect the operation of the impoundment. The dispersion of clays may be delayed if sufficient soluble Ca/Mg minerals are available to off-set the Na effects.

5. **Direction of Flow:** As long as a hydraulic head is present, infiltrating water will continue to migrate in both vertical and horizontal directions until a barrier/pathway is reached which redirects the migration of the infiltrating water. As such, it is expected that there will be radial flow away from an impoundment until such a barrier/pathway is intersected.

6. **Extraneous Issues:** Landowner issues, existing infrastructure, proximity to the producing field, potential beneficial uses, site conditions, and regulatory requirements may define where an infiltration system will be sited, and may thus impact the five items listed above.

Data Collection for Geophysical Logging, LX Bar Creek Watershed, Wyoming

The first four issues will be further explored by presenting data on the chemical composition and character of clay mineralogy, the chemistry of the produced water in the infiltration system, the chemistry of the shallow groundwater in the PRB, and some of the geochemical reactions that have been identified in corollary systems in which interactions between the infiltrating water, the soil, and the shallow groundwater have been observed and modeled. Most of the later discussion is based on analysis that has been done within the PRB around coal mine tailings piles and coal tailings aquifers. By understanding these components this research may lead to a better understanding of the changes that occur near an infiltration system as these impacts relate to the infiltrating water, soil, existing groundwater, and infiltration rates.

The last two issues will be discussed separately; 1) in terms of theoretical flow of infiltrating water through the soil and bedrock and how it may impact aquifers at various depths, and 2) in terms of potential extraneous issues that may affect the siting of an infiltration system, which in turn may affect the impacts of the infiltration system or the level at which impacts can be moderated in real world settings.

CLAY MINERALOGY

The surface soils in the PRB are primarily clay mineral assemblages. Previous research in the Wyoming portion of the PRB identified smectite and illite-smectite as the dominant clay mineralogy (Flores, et al, 1990). Smectite clays are also termed "swelling clays" because the mineral structure of smectite is capable of taking water into their structure which results in the expansion of clay. These swelling clay minerals were noted as uniformly distributed in the fluvial sedimentary rocks of the PRB, and thus can be interpreted as a single smectitic population. Other clays such as illite, and kaolinite, which have different degrees of crystallinity, as well as minor interstratified clays (i.e., illite-chlorite, chlorite-smectite) were also found to be present (Flores, et al, 1990). U.S. Geological Survey research on the soils of the PRB and their suitability for irrigation determined that montmorillonite is the dominant species of smectite clay present in the PRB (USGS, 2002).

Montmorillonite

Montmorillonite is a 2:1 phyllosilicate mineral that forms in sheets; the clay's structure is constructed of a single dioctahedral sheet sandwiched between two tetrahedral sheets (thus the name, 2:1), with the dioctahedral sheet sharing the apical oxygens of the tetrahedral sheets. The dioctahedral sheet of montmorillonite consists primarily of trivalent aluminum (3+) and some divalent magnesium (2+), which may create a small deficiency in charge that results in a negative charge of the "internal surface" (Peterson, 1997). The two tetrahedral sheets consist primarily of silicon (4+) and oxygen (2-), in a ratio of 4 to 10 (Peterson, 1997). The tetrahedral sheets also create a deficiency in charge that results in a negative charge; however, since the oxygen atoms are shared with multiple silicon atoms, a positive charge is observed where molecular bonds have been broken at the "external surface" of the clay sheet. This lack of a balanced charge enables the montmorillonite to attract cations for "internal surface" ion exchange (i.e. between sheets) and anions for "external surface" ion exchange (Peterson, 1997). This condition and the effect of CBNG produced water infiltrating through soils rich in montmorillonite is discussed more fully in Section 2.4.

General Formulas for Typical PRB Clays

Table 2-1 provides a brief summary of the general formulas for montmorillonite, kaolinite, and some of the other clay species that may be found in the PRB. The formulas in Table 2.2 show kaolinite is composed of the cations, silicon and aluminum. Kaolinite is a 1:1 phylosilicate mineral that consists of a single sheet of corner connected silica tetrahedrae, connected by common apex oxygen atoms to a single sheet of edge-connected alumina octahedrae; therefore, it undergoes very little or no swelling when exposed to water (USGS, 2002). Montmorillonite has calcium and/or sodium (depending on the species of montmorillonite), aluminum, and magnesium as the dominant cations, and may swap these ions for those in waters that contact the clay through ion exchange. Ion exchange is dependent upon the concentration of ions in the solution (infiltrating water), as well as the charge and size of the ions. As produced water infiltrates the soil, the water enters the inter-layers between the microscopic sheets of the montmorillonite clay, swelling the clay up to 30%. This enables the infiltrating water to exchange cations with the clay, provided a balanced charge is maintained (Barak and Nater, 2003).

Table 2-1: Classification Scheme for Phyllosillicates Related to Clay Materials

Group	Subgroup	Species (general formula)
Kaolin Serpentine	Kaolin	**Kaolinite** $Al_2Si_2O_5(OH)_4$
Mica	Dioctahedral micas	**Illite** $(K, H)Al_2(Si, Al)_4O_{10}(OH)_2$
Smectite	Dioctahedral smectite	**Montmorillonite** $(Na, Ca)(Al, Mg)_6(Si_4O_{10})_3(OH)_6$
Chlorite	Di/Trioctahedral Chlorites	**Chlorite** $(Fe, Mg, Al)_6(Si, Al)_4O_{10}(OH)_8$

Source: Adapted from Appendix I, Table A3 of the Internet Glossary of Soil Science Terms and Amethyst Galleries, Inc.

In addition to clay minerals, salts are often present in the soils of the PRB due to its semi-arid setting. These salts have accumulated naturally as a result of meteoric water infiltrating, but having insufficient volume to allow for saturated flow to the underlying groundwater. As such the salts picked up by the meteoric water are parked in the shallow subsurface at the depth where saturated flow could no longer be maintained. Further mineralization may occur through dissolution or precipitation of minerals from the water to the soil if the water is under or super-saturated compared to the soil, and the geochemical reactions for precipitation or dissolution are not limited kinetically, stoichiometrically, or temporally.

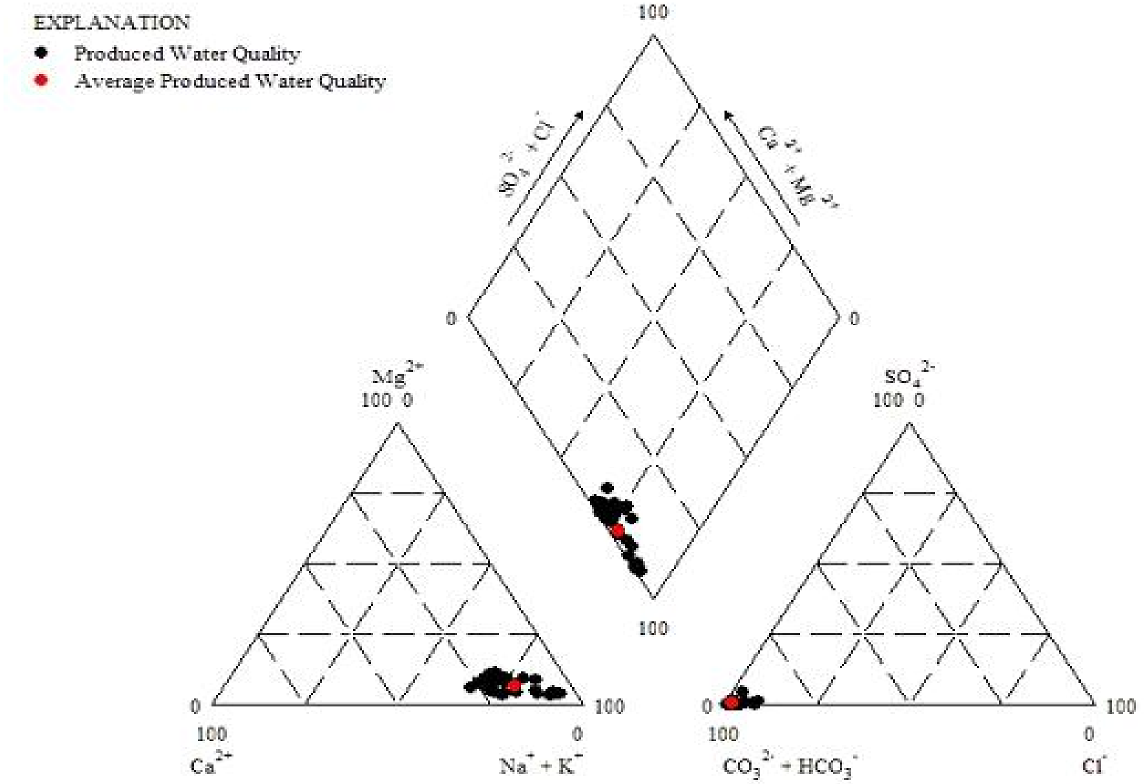
PRODUCED WATER CHEMISTRY

The quality of the water produced from CBNG development in the PRB varies between the numerous producing coal seams and across the basin within the same coal seam. In general, produced water quality has been more suitable (based on TDS and SAR) for beneficial use in the southeast and east portion of the basin (ALL Consulting, 2003). As drilling operations have moved west and northwest, the quality of the produced water from the coal seams has decreased, in part because the producing coals are at greater depths. The chemistry of the produced water may include various cations (positively charged ions), anions (negatively charged ions), and metals, but generally CBNG produced water shows very little scatter with respect to general constituents (See Figure 2-1). Table 2-2 is summary of the constituents that were identified by chemical analysis in a "typical" CBNG produced water sample. Table 2-2 shows both the major constituents which are typically identified during analysis and additional minor and trace elements that are also identified. CBNG water in the PRB is typically defined to be sodium/bicarbonate water based on the cation and anion present in the largest concentrations (See Figure 2-1).

The summation of the carbonate, bicarbonate, and hydroxyl in the water is typically referred to as the total alkalinity, and the summation of the cations and anions in the water is typically referred to as the TDS. TDS concentrations are typically used to assess water quality and the suitability of water for consumptive uses as well as other application uses. As TDS levels increase, the quality of the water and the number of appropriate beneficial uses (human consumption, irrigation, livestock and wildlife consumption, etc) decrease.

As the CBNG produced water is removed from within the anaerobic conditions of a coal seam to the surface where it is introduced to the atmosphere, the chemistry of the water will change as the water seeks to meet equilibrium with its new environment. Therefore, the chemistry of the produced water alone is not necessarily a reliable indicator of the chemistry of the water as it begins to infiltrate into the subsurface. Ongoing research is being conducted to document the change in the chemistry of produced water as it is exposed to the atmosphere and impounded (Jackson, et al, 2003). Initial results presented to date are for water samples that were collected and analyzed from twenty-three (23) infiltration impoundments (and their relative produced water discharge points) across the PRB. The twenty-three (23) infiltration impoundments were sub-divided into the five (5) major watersheds of the PRB (Power River, Tongue River, Little Powder River, Cheyenne River, and Belle Fourche River), with each watershed being represented with samples collected from producing wells and the infiltration impoundments.

Figure 2-1: Piper Diagram of CBNG Produced Water from Coal Seams in Montana and Wyoming



Data, Rice et al, 2000.

Table 2-2: Ions Identified in CBNG Produced Water from Coal Seams in Montana and Wyoming

CATIONS	ANIONS
Calcium, Ca $^{(2+)}$	*Carbonate,* CO_3 $^{(2-)}$
Magnesium, Mg $^{(2+)}$	*Bicarbonate,* $HCO_3^{(1-)}$
Sodium, Na $^{(1+)}$	Sulfate, SO_4 $^{(2-)}$
Potassium, K $^{(1+)}$	Chlorine, Cl $^{(1-)}$
Hydrogen, H $^{(1+)}$	Nitrate, NO_3 $^{(1-)}$
METALS	Hydrogen Phosphate $HPO_4^{(2-)}$
Aluminum	Bromine, $Br^{(1-)}$
Arsenic	Hydroxyl, $OH^{(1-)}$
Barium	**METALS**
Cadmium	Selenium
Chromium	Zinc
Copper	Boron
Iron	Manganese
Lead	Molybdenum

Italics identify the dominant cation and anions in CBNG water.

A comparison of the major ion values from the produced water and water taken from the infiltration impoundments from the 2003 study by Jackson, et. al. is provided in Table 2-3. While the data in this table is valuable in accessing the overall trends in the individual watersheds, it should not be relied upon for determining site-specific anticipated impacts of an infiltration impoundment or impoundment system. Instead, the data in Table 2-3 can be used as an example to show how water chemistry can change while produced water is located in the impoundment. These changes result from CO_2 out-gassing, intake of O_2, and general interaction between the water and the atmosphere. This research by Jackson, et al, should be consulted for a more complete review of how the water chemistry in the infiltration impoundments compares to the water chemistry of the discharge points (Jackson, et al, 2003).

A CBNG operator can use this current research effort to predict how discharge water chemistry will change as it is impounded, thus providing a potential input for each constituent in a predictive or analytical model. These inputs will define the initial conditions of the infiltrating water chemistry, which, when coupled with the input of the mineral assemblage of the soils, should allow the model to predict the rate at which minerals will either dissolve into the infiltrating water or precipitate into the soil as the water infiltrates into the subsurface.

Table 2-3: Comparison of CBNG Produced Water in Coal Seams and Impoundments in Wyoming

Site		**EC**	**pH**	**Ca**	**Mg**	**Na**	**SAR**	**Cl^-**	**SO_4**	**Alk.**	**TDS**
Belle Fourche River		**µS**	**units**	**ppm**	**ppm**	**ppm**	**units**	**ppm**	**ppm**	**mg/L**	**mg/L**
Site 168	Well	1162	7.23	26.5	16.7	211	7.89	23	116	460	744
	Pond	1310	7.44	30.2	42.4	225	6.18	23	396	190	838
Site 169	Well	912	8.02	19.2	15.3	170	7.04	22	0.43	455	584
	Pond	1923	9.34	62.4	69.1	302	6.26	35	ND	270	1231
Site 173	Well	680	7.12	21.3	7.2	129	6.17	30	0.06	355	435
	Pond	1192	8.80	50.9	42.6	166	4.15	28	255	310	763
Site 174	Well	703	7.15	18.3	9.6	134	6.33	29	0.47	345	450
	Pond	707	8.08	21	9.3	132	6.01	27	0.53	340	452
Cheyenne River											
Site 170	Well	629	6.73	15.4	6.9	120	6.36	29	0.3	335	403
	Pond	710	10.0	7.3	4.4	143	10.3	16	0.4	350	454
Site 171	Well	660	6.8	20.6	10.7	115	5.14	26	0.31	325	422
	Pond	518	9.18	9.1	7.0	99	5.99	16	4.57	270	332
Site 172	Well	615	8.54	25.4	9.7	92	3.95	20	ND	195	394
	Pond	518	9.24	6.5	4.4	92	6.85	12	6.24	230	332
Site 170 (2)	Well	719	7.16	17.1	9.4	127	6.14	19	0.21	355	460
	Pond	708	7.86	20.1	9.6	136	6.24	18	0.23	355	453
Little Powder River											
Site 162	Well	1380	6.97	21.9	7.4	113	5.34	8.1	0.12	335	883
	Pond	1320	7.1	5.1	10.3	167	9.77	10	2.44	410	845
Site 163	Well	1564	7.42	13.6	27	306	11.1	18	0.16	800	1001
	Pond	1578	8.01	39.1	34	401	11.3	26	0.68	1080	1010
Site 164	Well	1595	7.24	20.2	13	156	6.69	7.2	0.13	425	1021
	Pond	1577	8.82	10.14	26	362	13.79	19	0.98	940	1009
Site 165	Well	1709	7.32	13.6	23	356	13.7	17	0.23	880	1094
	Pond	1705	9.43	6.2	11	173	9.63	7	1.13	425	1091
Site 166	Well	1918	7.06	24.1	35	362	11.1	19	0.64	965	1228
	Pond	ND	ND	7.8	33	732	25.6	46	2.52	1765	ND
Site 167	Well	1005	7.49	16.6	9.2	193	9.44	28	32.2	420	643
	Pond	929	8.75	10.8	7	198	11.5	28	19.9	450	595
Site 176	Well	1243	7.37	18.9	13.3	261	11.3	33	0.25	650	796
	Pond	ND	8.08	19.5	12.5	249	10.8	30	0.28	655	ND

Table 2-3: Comparison of CBNG Produced Water in Coal Seams and Impoundments in Wyoming (cont'd)

Site		**EC**	**pH**	**Ca**	**Mg**	**Na**	**SAR**	**Cl**	**SO_4**	**Alk.**	**TDS**
Powder River		**µS**	**units**	**ppm**	**ppm**	**ppm**	**units**	**ppm**	**ppm**	**mg/L**	**mg/L**
Site 177	Well	3050	7.25	13.1	25	775	29.0	145	73.5	1680	1952
	Pond	3230	8.98	18.4	13	473	20.5	68	0.5	1095	2067
Site 179	Well	3010	7.52	14.8	18	708	29.4	124	0.35	1675	1926
	Pond	2990	8.5	4.7	8.7	442	27.9	61	0.46	1045	1914
Site 180	Well	1117	8.2	3.7	0.6	86.2	11.0	6.3	0.12	200	715
	Pond	1581	8.01	8.3	2.4	235	18.5	15	1.08	540	1012
Site 181	Well	2540	8.62	5.7	6.5	364	24.8	1.0	1.44	830	1626
	Pond	2790	8.95	4.9	8.7	347	21.8	13	73.0	735	1786
Site 182	Well	2200	7.14	7.9	16	569	26.9	22	0.1	1310	1408
	Pond	2370	8.28	5.0	8.7	368	23.0	12	0.7	840	1517
Site 183	Well	2750	7.18	12.1	7.2	366	20.6	11	0.03	880	1760
	Pond	2830	8.43	13.0	16	712	31.2	31	4.39	1635	1811
Tongue River											
Site 184	Well	1674	7.81	4.1	1.5	313	33.6	45	6.35	670	1071
	Pond	1767	8.76	2.6	2.3	379	41.3	57	27.2	810	1131
Site 185	Well	1740	7.89	3.8	1.3	297	33.6	41	0.3	675	1114
	Pond	1962	9.22	3.6	5.1	411	32.6	63	30.5	895	1256
Site 186	Well	2200	3.14	8.9	4.4	340	23.3	67	1045	0	1408
	Pond	1932	7.31	10.7	4.5	358	23.1	66	321	300	1236
Site 187	Well	1888	7.88	3.7	0.9	345	41.7	49	1.23	720	1208
	Pond	2100	8.99	2.9	2.1	407	44.4	52	8.74	875	1344
Site 188	Well	1824	7.91	3.5	0.9	351	43.3	43	0.26	760	1167
	Pond	1943	9.02	4.0	1.2	398	44.8	52	0.35	875	1244

Shaded locations show sites in which water quality appears to have declined from producing well to pond

.

Existing groundwater present in an area may be in equilibrium with respect to the clays and other mineral assemblages present in an aquifer, but when the existing waters are displaced or mixed with infiltrating water the resultant groundwater may become under-saturated or super-saturated with respect to the clays and other mineral assemblages in the area. Because of this phenomenon it is not always wise to make general determinations of whether produced water is super-saturated or under-saturated relative to different mineral assemblages based solely on the chemistry of the produced water, as the constituents present in the soils may dissolve into the infiltrating water or minerals may precipitate from the water to the soil. The degree to which dissolution and precipitation of minerals will occur is dependant on site-specific soil, groundwater, and infiltrating water conditions as they relate to one another. It is important to understand that these systems are dynamic and that the conditions that exist at any one time are a reflection only of that timeframe and may change considerably after infiltration has begun.

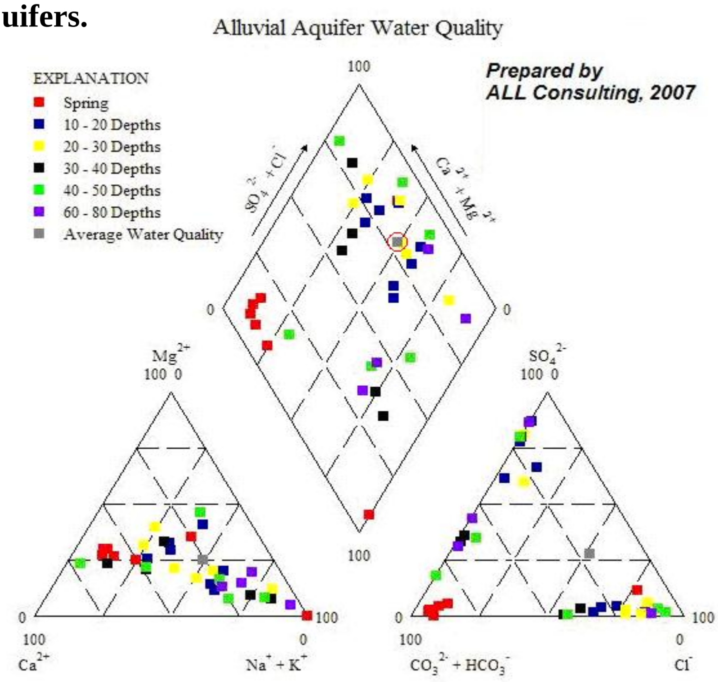
DEPTH TO GROUNDWATER AND WATER CHEMISTRY

In addition to the quality and quantity of infiltrating water and the mineralization that may occur from the soils beneath the infiltration system, the distance that infiltrating water travels through these materials before it reaches groundwater and the chemistry of the groundwater prior to mixing will also affect how the infiltration system impacts the overall water quality and the surrounding environment. A monitoring well, piezometer, or lysimeter can be installed in order to ascertain the depth to groundwater and to collect a sample of the groundwater that can be tested in a laboratory to determine the existing groundwater chemistry. The monitoring structure installed can also be used as part of the baseline study of the site as well as for monitoring the site once operations have commenced. The *Siting, Design, Construction and Reclamation Guidebook for Coalbed Natural Gas Impoundments* (ALL, 2006) should be consulted for more information on establishing a baseline study and monitoring program.

Once the existing groundwater chemistry and depth to groundwater are known, they can be input into the predictive or analytical model to define the initial conditions of the groundwater. These inputs allow for predictions of the resultant groundwater chemistry, both spatially and temporally, once the infiltrating water begins to mix with it. These inputs can also be used to account for the dynamic changes in the mineralogy of the saturated soil below the water table once mixing has begun.

Three geologic formations are present in the Powder River Basin that are recognized as being shallow groundwater aquifers. The three formations identified include the Alluvial, Fort Union, and the Wasatch aquifers. Water quality in these aquifers varies regionally and with respect to the vertical depth at which the aquifer is encountered. Background groundwater quality data collected by the USGS from monitoring wells completed in these aquifers was used to compare and evaluate impacts from CBNG produced water impoundment infiltration and the resultant effects of those systems on groundwater quality. The USGS data for each aquifer is plotted by depth on Figures 2-2 through 2-4, as discussed below.

Figure 2-2: Piper Plot for Water Samples Collected by the USGS from Monitoring Wells completed in Alluvial Aquifers.



The depth at which the data was collected for each aquifer appears to be a critical factor in the reported groundwater quality. The differing water quality for each depth can be compared to water quality data collected from monitoring wells located in the area of CBNG impoundments. Comparisons of historical and current water quality should show impacts to groundwater quality created by infiltration impoundments. Water quality data for the three aquifers encountered in the PRB in this study were plotted on Piper diagrams to evaluate the historical water quality.

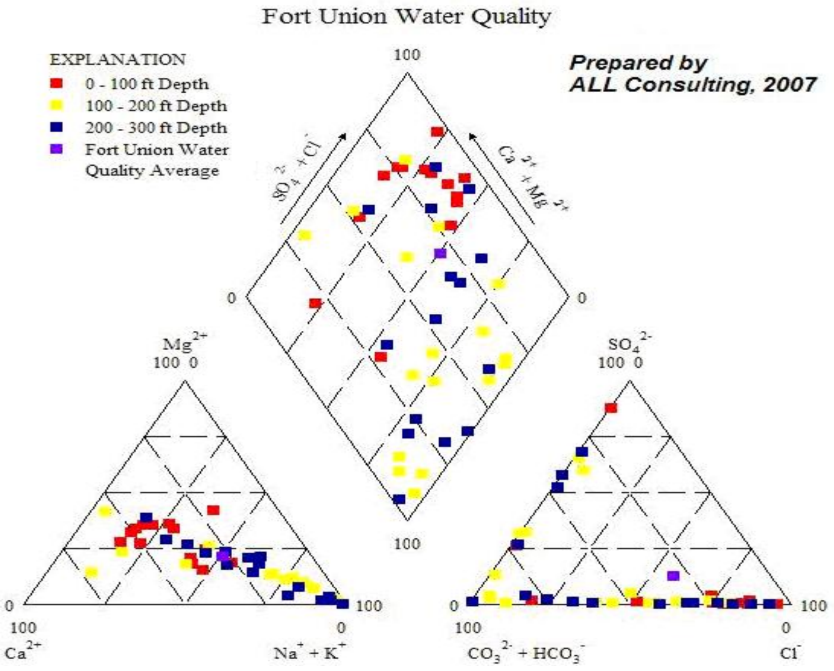
Alluvial Aquifer

Data used to produce the Alluvial Aquifer Piper diagram was collected from 1950 through 1981 at various locations and depths. The average water quality for the Alluvial aquifer can be characterized from this data as a sodium/potassium chloride water. Figure 2-2 shows the wide range of water quality collected for this particular aquifer. Certain observations can be made from this water quality data based on the depth at which the aquifer was encountered. Gradual movement from a calcium dominated water to sodium dominated water with increasing depth can be seen in the cation triangle of the plot. The anion composition plot shows sporadic distribution for the dominating anion component, but movement away from the dominate bicarbonate anion with increasing depth is evident.

Fort Union Aquifer

Data used to produce the Fort Union Piper diagram (Figure 2-3) were collected from 1950 through 1980 at various locations and depths. From the Piper diagram plot, the average water quality for the Fort Union aquifer can be characterized as a sodium/potassium chloride water. As with the Alluvial aquifer, depth plays an important role in the aquifer water quality. In areas where the aquifer depth is less than 100 feet, calcium is seen as the dependant cation, while chloride is the dominant anion. Increasing depth shows movement toward a sodium/potassium dominant cation. Unlike the Alluvial aquifer, anion migration in the Fort Union Aquifer is toward the bicarbonate species with increased depth.

Figure 2-3: Piper Plot for Water Samples Collected by the USGS from Monitoring Wells completed in the Fort Union Formation.

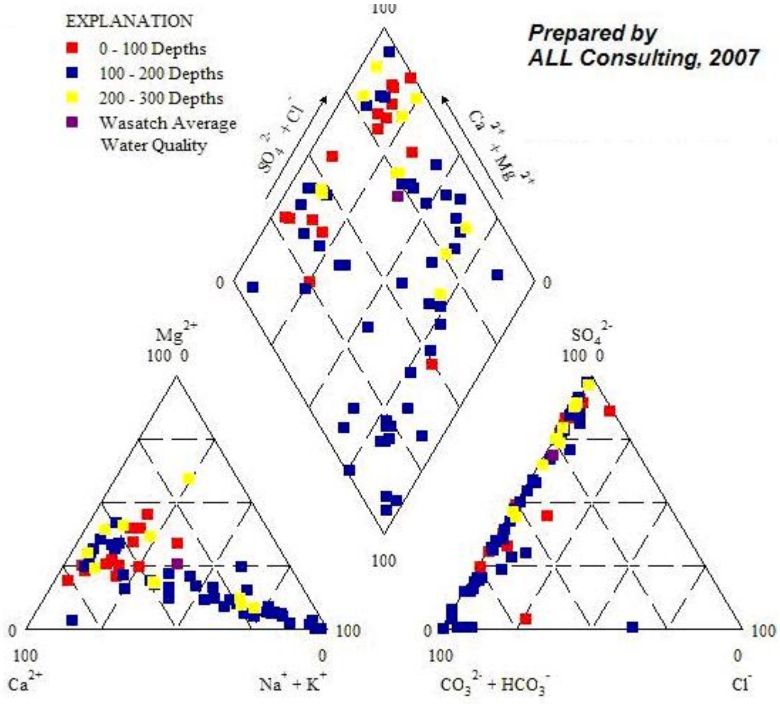


The differing water qualities within the same aquifer by depth demonstrate that average water quality data alone can not be used to compare with current monitoring water quality data in accessing potential impacts from infiltration. A visual inspection of the figure shows that reliance of the average water quality data point is ineffective because of the erratic data points spread throughout the diagram.

Wasatch Aquifer

Data used to produce the Wasatch Aquifer water quality Piper diagram (Figure 2-4) were colleted from 1949 through 1980 at various locations and depths. The data in Figure 2-4 can be utilized to determine the dominating cation and anion species for the Wasatch Formation. The data shows sulfate as the dominant anion species for the Wasatch Formation. The data shows sulfate as the dominant anion while there is an apparent lack of dominance between the three major cations. The projected average water quality shows that the water can be described as calcium/magnesium sulfate water.

Figure 2-4: Piper Plot for Water Samples Collected by the USGS from Monitoring Wells completed in the Wasatch Formation.



Similar to the Fort Union water quality data, an average water quality value for the Wasatch is not a good indication of the typical water quality to be expected by depth. Shallow waters of the Wasatch tend to be characterized as calcium bicarbonate waters, while deeper waters of the aquifer vary in dominance between sulfate and bicarbonate, but seem to be more highly influenced by the sulfate anion.

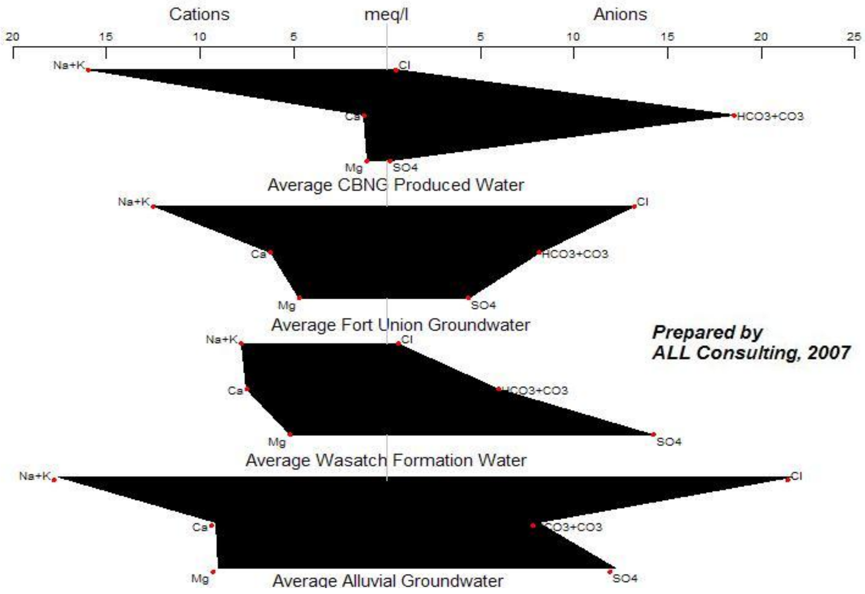
Another means to compare the variations in average water quality from the three formations to CBNG produced water is via a stiff diagram. The data in Figure 2-5 shows the average water quality for the three shallow formations in the PRB and average water quality for CBNG produced water in the PRB. This data is presented to facilitate a comparison of the geochemistry for those impoundments in which a historical record of water quality data is not available to show long term alterations to water quality.

Generally as infiltrating water moves further and further away from the infiltration system, it will have less and less of a measurable impact on the depth to and chemistry of the groundwater system until at some point the impact is immeasurable. Therefore any predictive model should utilize these inputs, along with hydraulic conductivity data of the soils to forecast the horizontal and vertical extent of the impact from the infiltrating water on the groundwater chemistry and the depth to groundwater. (A radially decreasing “mound” in the groundwater surface is typically observed beneath infiltration impoundments). This will allow the CBNG operator to predict the approximate radius of influence an infiltration system may have on the existing groundwater. If the radius of influence intersects a surface water body (stream, creek, river, etc) then there is potential that surface water quality will be impacted from the infiltration system. A further discussion of this scenario is included in the succeeding section.

GEOCHEMICAL REACTIONS

The equilibrium equations that govern the behavior of the geochemical reactions in the coal spoils soil and water have been developed by scientists and researchers to explain the fate and transport of chemicals in these natural media and are considered useful in this analysis (Martin et.al., 1988). Understanding equilibrium dynamics of several key constituents which are present in the infiltration water from the Wasatch and Fort Union Formations may help impoundment operators to identify the extent to which dissolution or precipitation may occur under an infiltration system fed by produced water from these intervals. By understanding the extent of dissolution or precipitation, an operator may be able to identify the extent to which geochemical alterations will change the quality of groundwater as it infiltrates through the subsurface materials beneath an impoundment.

Figure 2-5: A Stiff Diagram displaying Water Quality for the Shallow Aquifers in the Powder River Basin



Prepared by ALL Consulting, 2007

Formation of Carbonic Acid, Bicarbonate, Carbonate in Infiltrating Water

Water absorbs carbon dioxide readily when exposed to the atmosphere; when the carbon dioxide is induced under pressure, water is capable of absorbing even greater concentrations of carbon dioxide. The formation of carbonic acid is a result of carbon dioxide dissolving in water. As pH of water increases, carbonic acid dissociates partially to form bicarbonate and carbonate ions, as well as positively charged hydrogen ions. Figure 2-6 shows the dominant carbonate species relative to the pH of waters. The following equations represent the formation of carbonic acid, bicarbonate and carbonate:

- $H_2O + CO_2 \leftrightarrow H_2CO_3$ (Carbonic Acid)
- $H_2CO_3 \leftrightarrow H^+ + HCO_3^-$ (Bicarbonate)
- $HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$ (Carbonate)

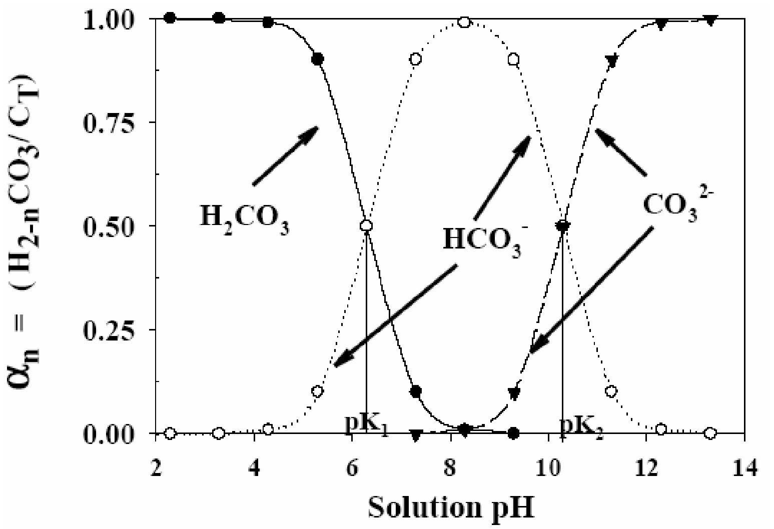


Figure 2-6: The Distribution of Carbonate Species as a Fraction of the Total Dissolved Carbonate in Relation to Solution pH

As can be see in Figure 2-6, bicarbonate is the dominant species for a pH range between pK_1 (~6.1) and pK_2 (~10.1), which is a typical range of pH for natural groundwater. The pH for CBNG produced water in the PRB varies from 6.7 to 8.2 at the wellhead and from 7.1 to 10.0 in infiltration systems (Jackson, et al, 2003), thus the CBNG produced water for the PRB should be considered dominant in bicarbonate. The dynamics of the carbonic acid system contributes to the ability of water to keep cations (such as calcium, magnesium, sodium, and potassium) in solution. The reactions identified above are reversible (represented by the double arrow) such that as the pH changes, the system can move from the intake of CO_2 and the change of carbonic acid to bicarbonate and carbonate; back to the formation of bicarbonate and carbonic acid; and the release of CO_2.

Carbonates, Sulfides, and Oxides in Soils

Carbonates, sulfides, and oxides are commonly found in the PRB soils and bedrocks. These mineral assemblages have a varying affinity to dissolve in water, depending on the chemistry of the infiltrating water. The geochemical formulas shown in this section assume that the water is free of alkalinity, and thus focuses on the dissolution of the mineral assemblages in pure water. As the cations and anions in the groundwater increase, the mineral assemblages may precipitate from the infiltrating water. The ability of these mineral assemblages to either dissolve or precipitate is depicted with a double arrow which represents reversibility of the indicated reaction.

Calcite and dolomite are the two carbonate species most commonly observed in the sediments of the PRB. Calcite contributes calcium and bicarbonate to the infiltrating water, while dolomite contributes magnesium, calcium, and bicarbonate to the infiltrating water. The following equilibrium equations represent the dissolution and/or precipitation of calcite and dolomite:

- Carbonates
    - Calcite ($CaCO_3$)
        - $H_2O + CaCO_3 \leftrightarrow Ca^{2+} + HCO_3^- + OH^-$
    - Dolomite ($MgCa(CO_3)_2$)
        - $2H_2O + MgCa(CO_3)_2 \leftrightarrow Mg^{2+} + Ca^{2+} + 2HCO_3^- + 2OH^-$

Gypsum, barite, magnesium sulfate (Epsom salts), and ferrous sulfate as well as certain sulfides and oxides have all been found in the soils of the PRB. The following equilibrium equations represent the dissolution and/or precipitation reaction equations for such common sulfates, sulfides and oxides:

- Sulfates
    - Gypsum ($CaSO_4$)
        - $H_2O + CaSO_4 \leftrightarrow Ca^{2+} + HSO_4^- + OH^-$
    - Barite ($BaSO_4$)
        - $H_2O + BaSO_4 \leftrightarrow Ba^{2+} + HSO_4^- + OH^-$
    - Magnesium Sulfate ($MgSO_4$)
        - $H_2O + MgSO_4 \leftrightarrow Mg^{2+} + HSO_4^- + OH^-$
    - Ferrous Sulfate ($FeSO_4$)
        - $H_2O + FeSO_4 \leftrightarrow Fe^{2+} + HSO_4^- + OH^-$
- Sulfides
    - Pyrite (FeS_2)
        - $FeS_2 + H_2O \leftrightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$
- Oxides
    - Iron Oxide (Fe_2O_3)
        - $Fe_2O_3 + 2SO_4^{2-} + 4.5C\ H_2O + 1.5\ H_2O \leftrightarrow 2FeS + 4.5HCO_3^- + 0.5\ H^+$

Cation Exchange in Soils

Cation exchange capacity (CEC) is a measure of the ability of a soil to retain and hold positively charged cations against the forces of leaching of these cations into the infiltrating water. As mentioned previously, montmorillonite has been found to be the predominant species of clay in the PRB, so it will be used for this discussion of how the cations in the clay can be exchanged with similar cations in the infiltrating water, resulting in changes to the infiltrating water quality and mineralization in the soils.

Calibrating Down-hole Geophysical Tools, LX Bar Creek Watershed, Wyoming

The interlayer space (the space between montmorillonite sheets) is expanded as it becomes hydrated with infiltrating water. The separation between sheets which relates directly to the amount of swelling varies depending on the cations present in the montmorillonite interlayer, and the ionic strength and chemistry of the infiltrating water (Barak and Nater, 2003). In addition, it is fairly easy to exchange interlayer cations with other cations in solution if there is an abundance of one cation in the infiltrating water (i.e. the water is super saturated with respect to that cation).

Cations in the infiltrating water may exchange with the calcium, magnesium, and/or sodium in the montmorillonite, thus causing an increase in those cations in the water. This can result in a change to the chemical nature of the water. For example, a water which is dominated by sodium (+1) ions may exchange sodium at a 2:1 ratio for calcium (+2) or magnesium (+2) resulting in a decrease in the waters salinity. The montmorillonite clays of the PRB can contain either calcium, sodium, or both in the interlayer space. Sodium dominant montmorillonite is characterized by a higher swelling capacity and lower permeability than calcium dominated montmorillonite. However, calcium dominated montmorillonite clays are more susceptible to the cation exchange of sodium from infiltrating water for the calcium or magnesium cations present on the surface of the clays (USGS, 2002). Such exchanges of sodium for calcium and magnesium would result in overall decreases in infiltration rates with the increased swelling capacity and lower permeability (USGS, 2002).

This change in the infiltration rate can ultimately impact the effectiveness of the infiltration system, as the amount of produced water able to be managed by the infiltration system may decrease over an extended operational period. It appears that the time of effective infiltration is extended by the presence of Ca or Mg bearing natural salts, since the dissolution of these minerals will decrease the relative abundance of Na in the infiltrating water. Furthermore, the increase in TDS of the infiltrating water may result in decreased quality of the shallow groundwater aquifers (assuming the shallow groundwater has a lower TDS than the infiltrating water) as the infiltrating water mixes with the shallow groundwater. Alternatively, if the TDS in the shallow groundwater is higher than the TDS of the infiltrating water, the quality of the groundwater after mixing may be better than the existing quality of the shallow groundwater.

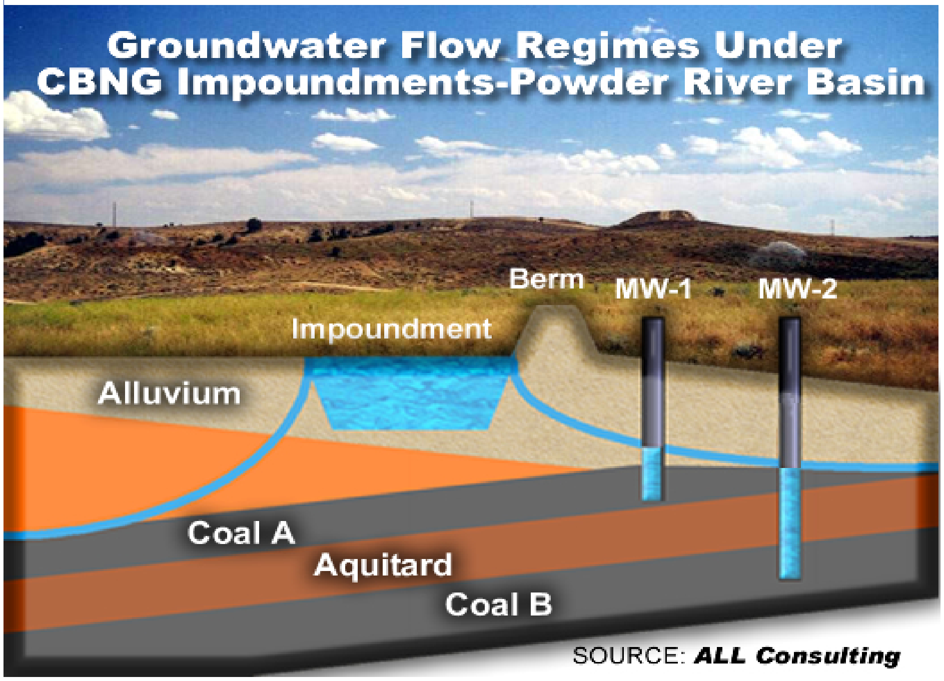
Another consideration is the reversal of previously identified geochemical alterations in groundwater chemistry that occurs as waters migrate downward deeper into the Wasatch Formation. Bartos and Ogle (2002) noted that chemical alterations of groundwater moving through the Wasatch Formation show an evolving or cyclic alteration which transforms this shallow groundwater into sodium-bicarbonate type water in the deeper sands of the Wasatch and the coal seam aquifers.

DIRECTION OF GROUNDWATER FLOW

This section discusses the hydrogeologic theory of CBNG water infiltrating through the bottom of an infiltration impoundment into a saturated soil system and down into existing shallow groundwater. The information presented in this section assumes that the below surface soils and geologic materials present under the infiltration impoundment are in a saturated condition. The theory presented here conceptualizes the hydrogeologic conditions which result when infiltrating water either continues to migrate vertically into deeper zones or migrates horizontally. There are a variety of textbooks which discuss such groundwater flow including Fetter (1994), Freeze and Cherry (1979), and Domenico and Schwartz (1998). These texts can also provide additional conceptual details as well as the mathematics associated with the technical discussion included below.

For the infiltration system shown in Figure 2-7, water outflow is bidirectional, with both vertical and horizontal components. Two well established flow equations define the horizontal flow in the upper unconfined zone and the vertical flow component through the confining zone into a lower aquifer. As it will be shown these two equations can be used to evaluate the flow of groundwater under an infiltration impoundment and to determine when resulting conditions would raise potential regulatory concerns. The two principal regulatory concerns identified are: the potential for infiltrating produced water being discharged into a surface water body, and the alteration of high quality groundwater through mixing of such waters with infiltrated produced water. The concern relative to horizontal flow may be greater as the migration and ultimate potential discharge of the groundwater / produced water mixture occurs at some distance from the infiltration system at the interface of down-gradient surface water bodies (rivers, streams, or lakes). While a significant vertical flow component could result in an increased likelihood of the infiltrating water coming into contact with deeper groundwater aquifers, which, in the PRB, may potentially contain higher quality waters than the shallow groundwater aquifers and, thus have a greater net impact to water quality resources.

Figure 2-7: Theoretical Groundwater Flow Diagram



SOURCE: **ALL Consulting**

Under an infiltration system such as the one diagramed in Figure 1-4, the components of the vertical and horizontal flow systems are interrelated when the system reaches saturation. There are several assumptions which must be considered when considering the analysis of this type of infiltration impoundment or impoundment system. First, the water level in the infiltration impoundment will be maintained relatively constant so that at some time after infiltration has been initiated, h_1 (the hydraulic head) would become a constant. In other words, once infiltrating water has saturated the soil column below the infiltration impoundment, the hydraulic head is maintained by inflow. In real world terms, this assumption indicates that as production from a CBNG field declines over time, the operator will choose to continue to use the impoundment as a primary source for water management. This assumption also includes the premise that the rate of infiltration through the bottom of the infiltration impoundment is relatively constant and that the outflow is maintained (i.e. there is no de-flocculation of the clays causing the bottom of the infiltration impoundment to seal itself).

Secondly, the shallow unconfined aquifer and the lower confined aquifer are not in direct hydraulic communication. This assumption implies that a confining zone between the two water bearing zones is sufficient in lateral extent in the area of the infiltration impoundment or system to limit the migration of water between these two zones such that a differential pressure head has been established between these two water-bearing zones. This assumption can be observed in the field by evaluating the water levels of monitoring wells completed in each water zone; the pressure head of the lower zone can be negative or positive relative to the confining zone. (Note: if the goal is to limit the downward migration of infiltrating water, a positive pressure head would be more effective.)

The flow or movement of groundwater in a saturated system is defined by the empirical law of groundwater flow, Darcy's Law.

Darcy's Law states that: $Q = KIA$

where Q is discharge or outflow rate (cubic feet per second), K is the hydraulic conductivity (unitless), I is the hydraulic gradient (feet/feet) and A is the cross sectional area (square feet). The two components for infiltrating water flow from the bottom of an infiltration impoundment can be defined by the following derivations of the Darcy's Law equation.

The vertical flow component through a confining zone can be expressed as:

$$Q_v = K_{2v} * (h_1 - h_3)/l * A_v$$

where Q_v is the flow through the lower confining zone, K_{2v} is the hydraulic conductivity of the confining zone in the vertical direction, h_1-h_3 is the hydraulic head difference between the water level in the infiltration impoundment and the pressure head in the aquifer just below the confining zone, l is the distance between the infiltration impoundment and a monitoring well or piezometer measuring the head in the lower confined aquifer, and A is the cross sectional area through which the flow is observed (typically this can be assumed to be a unit area such as 1 square feet).

The horizontal flow component in the upper zone can be expressed as:

$$Q_h = K_{1h} * (h_1 - h_2)/l * A_h$$

where Q_h is the horizontal flow away from the infiltration impoundment in the shallow zone, K_{1h} is the hydraulic conductivity of the shallow aquifer in the horizontal direction, h_1-h_2 is the head difference between the water level in the infiltration impoundment and the hydraulic head in the aquifer above the confining zone and l is the distance between the infiltration impoundment and the monitoring well, A is the cross sectional area through which the flow is observed (again this can be assumed to be a unit area such as 1 square feet).

Both Q_v and Q_h, will have some quantity of flow, and an infiltration impoundment or impoundment system could be sited in a geologic system where either of these components could be maximized or minimized to effect control over potential impacts. Theoretically, below most impoundments and impoundment systems a higher Q_h component would be expected such that water flows down through the bottom of the infiltration system and extends horizontally in the shallow unconsolidated aquifer above the confining zone. This is due to the fact that the K_v of the confining zone would be several orders of magnitude smaller than the K_h of the shallow aquifer (for most geologic materials the vertical hydraulic conductivity is typically an order of magnitude smaller than the horizontal hydraulic conductivity when the medium is saturated). In the case of the surficial geology of the PRB, the shallow unconfined aquifer could be alluvium, colluvium, clinker or other unconsolidated sediments; the confining zone could be an interbedded clay or bedrock shale zone.

The first relationship between the horizontal and vertical components can then be inferred between Q_v and K_h, such that, as K_h is increased Q_v would be correspondingly decreased. This implies that the greater the potential for flow in the horizontal direction in a saturated shallow aquifer the less flow would be realized in the vertical direction through the confining zone. In other words an infiltration system site with a greater potential for horizontal migration would have a corresponding lesser potential for vertical flow through a confining layer. So if an infiltration system site is constructed where the upper materials are alluvium or weathered sandstone overlying a thick clay or shale, the infiltrating water would pool and migrate horizontally down-gradient in the upper zone at a much greater rate than that which would infiltrate downward into the lower confined aquifer.

Secondly, as A_v is related to the ratio between K_h/K_v, as the potential for flow along the horizontal plane increases relative to the potential for flow in the vertical plane, the area through which the flow in a vertical direction decreases. So as water migrates horizontally along the saturated thickness of the shallow aquifer, there would be a smaller cross section area of water to be in contact with the confining zone. Thus in a situation where the ratio between the horizontal and the vertical hydraulic conductivity is low, a larger area of contact would exist as the water pools across the top of the confining zone.

Hollow Stem Auger Boreholes in the Prairie Dog Creek Watershed, Wyoming

This discussion does not consider several additional factors which, depending on site specific conditions, may need to be addressed. For instance, differences may exist in the density of water that is infiltrating (density increases as TDS increases) versus the density of the existing groundwater. In a situation where the TDS in the infiltrating water increases to that of salt water brine or greater, density differences between the two waters may have a significant influence on fluid flow including the movement of high TDS water against the hydraulic gradient (Boutwell and Lawrence, 1988). Furthermore, research indicates that higher TDS waters, especially salty brines, can increase the permeability of confining units and decrease the breakthrough time to half that of low TDS water (Boutwell and Lawrence, 1988). In cases where there are considerable increases in TDS as a result of the dissolution of salts present in the shallow materials, the potential for this water to pass through a thin confining zone can be increased considerably and should be considered in siting of infiltration impoundments located were such conditions exist.

It should also be noted that within the Wasatch and Fort Union Formations, there is considerable heterogeneity and anisotropy present in the discontinuous sandstone lenses which are surrounded by fine-grained materials (Bartos and Ogle, 2002). These heterogeneities influence the actual direction of groundwater flow; the USGS has noted that these heterogeneities result in much of the Wasatch and Fort Union Formation groundwater flows to be predominantly horizontal in direction (Bartos and Ogle, 2002).

EXTRANEOUS ISSUES

There are various extraneous issues that may dictate the siting of an infiltration impoundment or impoundment system, which will in turn affect the anticipated impacts of such a system on the soil and groundwater, as discussed above. In general, these issues consist of landowner relations, proximity to existing infrastructure and producing wells, potential for beneficial uses (stock watering, irrigation, etc), geomorphology, vegetation, and regulatory requirements. These issues are briefly discussed here, and are more fully discussed in the *Siting, Design, Construction and Reclamation Guidebook for Coalbed Natural Gas Impoundments* (ALL, 2006) and in the *CBM Beneficial Uses Handbook* (ALL, 2003).

Landowner Relations

The operator may choose to encourage a positive relationship with the landowner in regards to siting an infiltration system in order to promote beneficial uses for the landowner during CBNG production operations and after operations have ceased. Therefore, communication with the landowner and identifying landowner needs are important in identifying the location for a potential infiltration system. Many ranchers in the PRB have been willing to accept as much water as their current livestock can consume; in part because of the current drought condition, or for others the additional supply of water may open new grazing land that was previously unavailable (ALL, 2003). In most instances where there are multiple sites considered for the location of an infiltration impoundment, while each site may be equally attractive to the operator in terms of operation and construction, the option most appealing to the landowner may become a determining factor to where the infiltration system is actually constructed.

Proximity to Existing Infrastructure

The location of existing infrastructure, such as produced water pipelines, access roads, and producing CBNG wells may play an important role in the siting of an infiltration impoundment. Future proposed in-fill or extensional drilling locations may also contribute to the decision making process as where to site an infiltration impoundment. By choosing a site in a location that will utilize existing infrastructure, an operator may be able to prevent unnecessary disturbance to the surface associated with installing new pipelines and access roads.

Potential Beneficial Uses

In an arid region such as the PRB, there are various beneficial uses for the produced water that can add value from that product to both the landowner as well as the CBNG operator. As an example, additional habitat can be created for fish, waterfowl, livestock, and other animals by providing an additional source of water where water resources at the surface are normally limited. Additionally, using CBNG produced water for the irrigation of crops and grazing pastures can increase the yield for farmers for their crops and increase forage available to livestock for the ranchers. Furthermore, CBNG operators can add value to their CBNG projects by using the CBNG produced water to support on-going operations (dust control, drilling mud, well treatments, concrete construction, etc). Therefore, the nature and extent of the anticipated beneficial uses of the produced water may affect the siting of an infiltration impoundment.

Geomorphology

Geomorphology can impact the decision making process of where to site an on-channel infiltration system by assessing the potential impact a system may have on the stability of an existing waterway, and how nearby waterways may be altered as a result of the infiltration system construction and operation.

Vegetation

Vegetation can be used both during and after construction to protect slopes, uptake water from the soil, and establish a suitable and durable groundcover at the site. The type of vegetation used for an infiltration system will depend on the characteristics of the soil (geochemistry), climate, and permeability. For instance, certain plant types require higher water uptakes and thus are only present where soil permeability and soil moisture is high. In addition, permeability can facilitate nutrient uptake. However, excessive soil permeability can reduce water retention and/or nutrient uptake and significantly affect the viability of local vegetative populations. As such, vegetation endemic to the local area or region should be used when feasible and local soil conditions, to the extent possible, should remain consistent with pre-construction conditions. In terms of CBNG infiltration systems, certain vegetative species are more tolerant of higher salinity soils (halophytes) and thus may be more successful in this type of situation, especially when the local soil conditions are defined by low permeability.

Regulatory Requirements

The use of infiltration systems and impoundments associated with CBNG development is regulated by a variety of agencies at the state and federal level. The regulatory requirements of the various agencies that have jurisdiction specific to infiltration systems in the Powder River Basin can affect final siting requirements for an infiltration system, depending on which agencies have jurisdiction and the existing site conditions (soil, groundwater, and surface water quality, etc). A more detailed discussion of current regulatory requirements can be found in the *Siting, Design, Construction, and Reclamation Guidebook for Coalbed Natural Gas Impoundments* report (ALL, 2006).

ON-CHANNEL VS OFF-CHANNEL INFILTRATION SYSTEMS

On-channel infiltration systems are defined as any system constructed by building an embankment or dam across a stream, intermittent channel, or watercourse where the stream valley is depressed enough to permit the storing of 5 feet or more of water (USDA, NRCS, 1982a). The land slope may range from gentle to steep. Off-channel infiltration systems are defined as any system constructed by excavating a pit or dugout in a nearly level area outside of an existing stream channel or intermittent watercourse (USDA, NRCS, 1982a). Off-channel infiltration systems can be built in gently to moderately sloping areas where their capacity is obtained both by excavating and by building additional freeboard (USDA, NRCS, 1982b). A discussion of the technical and logistical benefits and limitations of each type of infiltration system is included in the *Siting, Design, Construction and Reclamation Guidebook for Coalbed Natural Gas Impoundments* (ALL, 2006). This section will focus on the inputs that can be included in an analytical model that defines how on-channel and off-channel infiltration systems behave as the water infiltrates into the subsurface beneath them.

Variable Infiltration Rates

The soil matrix beneath on-channel infiltration systems is unique due to the nature of where on-channel infiltration systems are constructed. Generally alluvium is present beneath an on-channel infiltration system, and this can be accounted for in an analytical model by providing the model with the necessary information to establish site specific infiltration rates. In comparison to the soils which may be present under an off-channel infiltration system, the presence of alluvium may result in a higher infiltration rates for on-channel infiltration systems.

The infiltration rate is the quantity of the produced water that infiltrates into the subsurface prior to the saturation of the soil column. Infiltration rates for both on-channel and off-channel infiltration systems can be accounted for in an analytical model by providing site-specific hydraulic conductivity and the average thickness for the soils directly beneath the infiltration system, as well as for any confining layer(s) beneath them. This data can be collected in the field using some simple methods to test the soils and aquifer systems. In most cases it will be necessary to assume that the confining layer(s) are continuous and extend far enough laterally to prevent infiltrating water to vertically migrate into deeper groundwater aquifers. If local evidence suggests less than a continuous nature to these layers, then such conditions could impact predictions for fluid dispersal or infiltration. Inputs such as these will define how a model or methodology is able to predict the spatial and temporal movement of the water as it infiltrates into the subsurface and reaches the shallow groundwater aquifer.

Variations in Geology and Mineralization

In addition to the variations in infiltration rates between on-channel and off-channel infiltration systems, variations in the composition of the soil which determines whether infiltrating water will dissolve or precipitate minerals can be accounted for in a predictive methodology or analytical model. Across much of the PRB, alluvium or alluvial soils beneath an on-channel infiltration system will have a different mineral make up than the soil beneath an off-channel infiltration system. Alluvium materials present in the PRB are seasonally flushed of mineral accumulations by spring snow melts which push volumes of surface water back into these systems. The mineral assemblage present in the soils beneath an infiltration system can be input into an analytical or predictive model, along with layer thickness, to define the ability of that soil to either precipitate minerals from the infiltrating water or dissolve minerals out of the soil into the infiltrating water. Of course, this is also dependant on the initial quality of the infiltrating water that moves through the system.

DISTANCE TO SURFACE WATER AND SURFACE WATER CHEMISTRY

In the arid PRB, surface waters (streams, rivers, creeks) may be fed by discharge from groundwater during dry periods. As mentioned in the previous section, if a surface water body is within the radius of influence of the infiltration system, as predicted by theoretical modeling, then there is a potential that the surface water chemistry will be impacted from the infiltration system. Therefore, the distance from the infiltration system to the closest down gradient surface water body is an important boundary condition that can be evaluated in a model to predict the likelihood of the infiltration system impacting the surface water. The chemistry of the surface water varies depending on the time of year and the current climatic conditions. Since the surface water chemistry is dynamic, the following considerations can be considered when developing a theoretical site model:

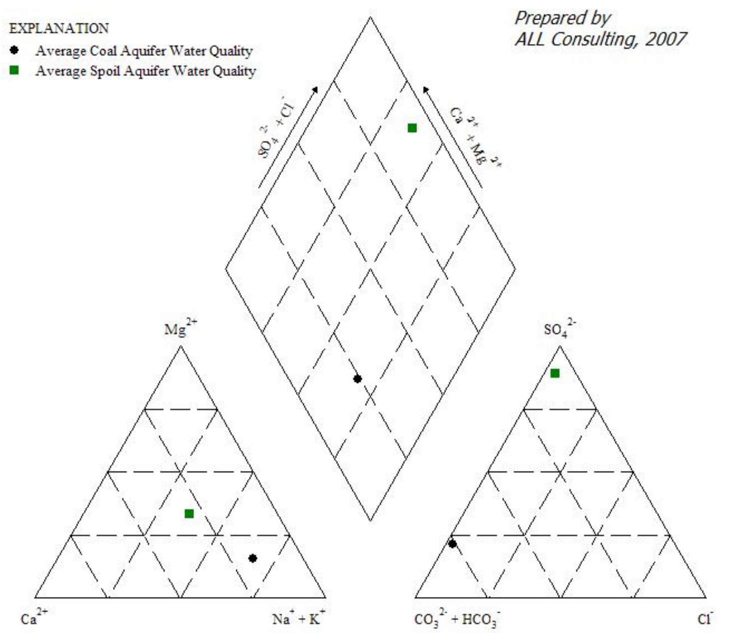
- Use a theoretical model in which the surface water chemistry is evaluated as an average value, taken from various samples collected throughout the year;
- Develop a theoretical model in which the surface water chemistry is a "worst case" scenario, by using the best water chemistry (i.e. lowest TDS) result as the surface water chemistry; or
- Develop a separate theoretical model for each individual surface water chemistry data point that represents the time of year that data was collected.

The combination of the distance to the surface water and the surface water chemistry inputs into the analytical model will allow for predictions relative to the likelihood of an impact to the surface water, and the resultant chemistry of the surface water would be after mixing if the infiltrating water did reach the surface water. These inputs will also allow the model to account for the dynamic changes in the mineralogy of the saturated soil adjacent to the surface water body once mixing has begun.

COAL MINE SPOILS- AN EXAMPLE OF GROUNDWATER ALTERATIONS

Previous research conducted by the USGS and state agencies within the PRB have shown that geochemical interactions occur from water infiltrating through the soils and bedrock of the PRB (Naftz, 1990; Bartos and Ogle, 2002; Larson, 1988; Martin et. al., 1988, McKinley, 2004; Wheaton and Brown, 2005; and Wheaton et.al., 2007). Prior to 2000, most of this research focused on identifying the quality of groundwater that would result from groundwater recharge and infiltrating rainwater interacting with coal mine tailings spoils. Coal mine tailings spoils are the overburden materials present above the mineable coal seams that are typically removed and stockpiled to allow access to the coal seams. The tailings materials are similar in geologic composition to those materials present in the shallow subsurface beneath CBNG impoundments in the PRB, primarily the Wasatch and Fort Union Formation lithology. Coal mine spoils aquifers develop as a result of coal mine reclamation where spoils materials are returned to "mined-out" regions and groundwater is allowed to infiltrate or flow laterally back into these materials. The disturbed soils have increased porosity and permeability which results in increased groundwater flow rates and infiltration in these areas. The disturbed soils also have increased surface areas which results in the groundwater having increased exposure to the surfaces of the soil materials, which allows for increased chemical interaction to occur.

Figure 2-8: Piper Diagram Showing Chemical Composition of Coal Aquifer and Spoil Aquifer Water Quality at the Cordero Mine, Wyoming

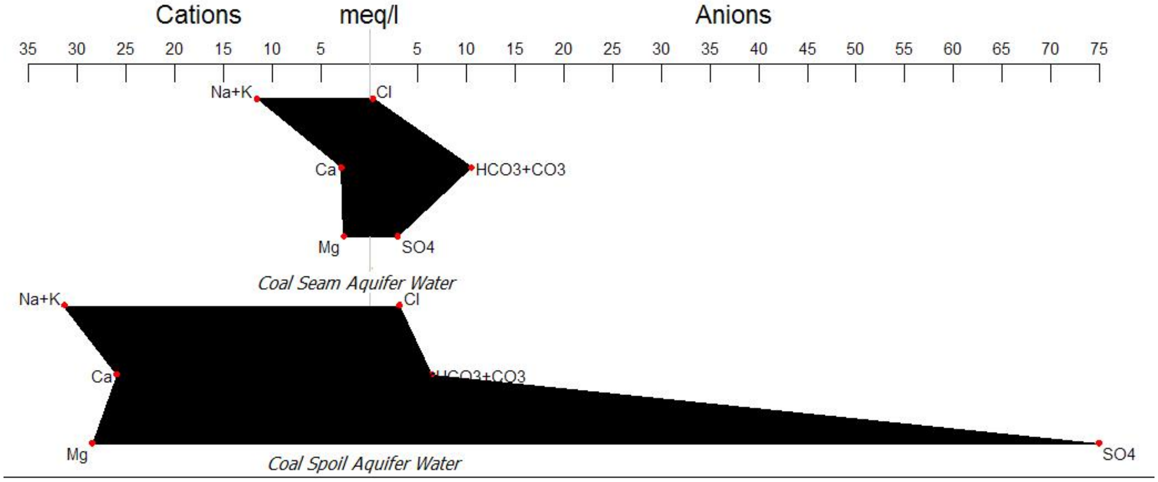


Data from Naftz, 1990.

Geochemical changes that have been observed in coal mine spoils aquifers for the Cordero Mine in the PRB of Wyoming are shown in Figures 2-8 and 2-9 (data from Naftz, 1990). Figure 2-8 shows the chemical nature of the two waters, 1) the coal seam aquifer (similar to CBNG water quality) and 2) the coal spoil aquifer water quality. The chemical changes which occur in the coal spoils cause the water to be altered from a sodium/bicarbonate water to a sodium, calcium, magnesium/ sulfate water. The stiff diagram in Figure 2-9 shows the degree to which the three cations and the anion, sulfate, increases as a result of interactions with soils materials in the coal mine spoils. The milli-equivalent concentration of sodium in the coal spoil aquifer water is nearly three times that of the coal seam aquifer water; both calcium and magnesium exhibit a nearly 10-fold increase. The anion changes include an approximately 30-fold increase in sulfate, a 10-fold increase in chloride, and 50% reduction in bicarbonate (Figure 2-9). The anion changes can be short term and have been shown to be negated after two to three pore volumes of flushing (National Research Council, 1990).

The USGS has researched the composition of the Wasatch and Fort Union Formations in order to identify the specific mineralogic composition of these materials to help understand the chemical interactions that are occurring in coal mine tailings systems. The research by Martin et. al.(1988) identified seven reaction sets of possible mineralogic and chemical phases for the overburden material which could result in the chemical changes that result during the recharge of spoils materials as shown in Figure 2-9. Table 2-4 shows the seven reaction sets that were identified as plausible phases for mass balance calculations in determining coalmine spoils chemical reactions

Figure 2-9: Stiff Diagram showing Chemical Composition of Coal Aquifer and Spoil Aquifer Water Quality at the Cordero Mine, Wyoming.



(Martin et. al. 1988).

These reaction sets provide the sources for the cations (sodium, calcium, potassium, and magnesium) and anions (sulfate, chloride, and carbonate sink) that are shown to increase in Figure 2-9.

These chemical reaction sets have been used in existing geochemical models, WATEQF and PHREEQ, to reproduce the chemical alterations of groundwater in coal spoil aquifers and to try to predict similar chemical alterations that would occur as CBNG produced water migrates downward from infiltration impoundments. Martin et.al (1988) determined that the seven reaction sets identified in Table 2-4 present a reasonable reaction model through mass balance analysis to explain the water-quality changes that occur during coal mine spoils aquifer recharge.

Table 2-4: Possible Reaction Sets for Geochemical Modeling of Surface Soils and Bedrock in the Powder River Basin.

Reaction Set	Plausible phases
1	Calcite, carbon dioxide, cation exchange, chlorite, goethite, halite, kaolonite, oxygen, potassium feldspar, pyrite, and silica
2	Carbon dioxide, cation exchange, chlorite, goethite, gypsum, halite, kaolonite, oxygen, potassium feldspar, pyrite, and silica
3	Calcite, carbon dioxide, cation exchange, chlorite, goethite, gypsum, halite, kaolonite, oxygen, potassium feldspar, pyrite, and silica
4	Calcite, cation exchange, chlorite, goethite, gypsum, halite, kaolonite, organic carbon, oxygen, potassium feldspar, and silica
5	Calcite, carbon dioxide, cation exchange, chlorite, goethite, gypsum, halite, kaolonite, oxygen, potassium feldspar, and silica
6	Calcite, carbon dioxide, cation exchange, chlorite, gypsum, halite, kaolonite, potassium feldspar, and silica
7	Calcite, cation exchange, chlorite, epsomite, gypsum, halite, kaolonite, potassium feldspar, and silica

Modified from Martin et. al. 1988.

THIS PAGE INTENTIONALLY LEFT BLANK

Summary of Documents Produced in Association with the Study of CBNG Impoundments

The following section provides a summary of three other documents produced under the Project DE-AD26-06NT02045 Coalbed Natural Gas Research performed by ALL Consulting for the United States Department of Energy. The three documents that were developed under this project address issues associated with the management of CBNG produced water. The first document summarized in this section addresses the issue of re-injection of CBNG produced water in the PRB. Re-injection or the lack of a requirement of re-injection by regulators has been used as a discussion point by Non-Governmental Organizations when commenting on the practices of the CBNG industry. The summary provided here addresses the technical aspects associated with potential for re-injection and injection of CBNG produced water to be successful in the PRB. The second paper summarized here addresses the issue of water statistics related to the PRB and CBNG produced water. A great deal of emphasis is placed upon the volumes of water that are produced over the lifetime of a CBNG producing well. This paper relates water statistics from everyday life to CBNG produced water volumes in an attempt to give an everyday perspective to some of the water statistics that are commonly addressed relative to CBNG development in the PRB. The final document summarized in this section of this report addresses the siting, design, construction, and reclamation of CBNG impoundments. This document is intent to provide a variety of best management practice type discussions regarding impoundments constructed in association with CBNG development in the PRB.

RE-INJECTION OF CBNG PRODUCED WATER IN THE POWDER RIVER BASIN

INTRODUCTION

Natural gas use in the United States has risen over the past decade and is expected to continue to be a prime source of energy for industrial power and heating, as well as for residential uses. This increased need for natural gas has prompted an increase in the exploration and production of unconventional gas resources such as CBNG. CBNG currently represents approximately 8% of the nation's natural gas production. As the development of CBNG expanded into the PRB of Wyoming and Montana, its development gained increased attention from local and regional stakeholders. This heightened awareness of CBNG production involves public concerns largely related to the management of the produced water associated with the gas production. These water management concerns include the withdrawal of large amounts of water from targeted coal seams, the potential waste of high-quality water resources, and the surface discharge of that water.

The management of the CBNG produced water resource in the PRB is accomplished through a variety of water management options including injection and re-injection. The issue of re-injection of that water back into the producing coal seam by way of Underground Injection Control (UIC) wells as an option for produced water management in the PRB has been supported by a number of special interest groups (NPRC 2004a, 2004b). Reports prepared by these groups suggest that re-injection is the only management alternative that will allow for sustainable development. In addition, an earlier report suggests re-injection is feasible in active CBNG producing areas (Schneider, 2001). However, reservations and concerns remain about the feasibility of this technology as a produced water management tool in the PRB.

Monitoring Well Drilling Prairie Dog Creek Watershed, Wyoming

Presented below is a brief review of the PRB and the water resources in the basin. Also presented is an analysis of the factors affecting re-injection of CBNG produced water in the PRB, including the constraints and parameters that need to be considered to effectively utilize re-injection as a water management option. These constraints include technical, management, environmental, regulatory, and economic considerations. In addition, the available re-injection options are reviewed and conclusions are presented.

POWDER RIVER BASIN AND COAL BED NATURAL GAS

The PRB extends from east-central Wyoming northward into southeastern Montana. Throughout the PRB there are federally owned and managed, Tribal, state owned, and private mineral interests. The natural gas and water is produced from Tertiary aged coals. The average range of depth for production is between 200 feet and about 2,500 feet, and water quality ranges from 250 mg/L to greater than 3,000 mg/L TDS with a mean of 850 mg/L. To date, the primary management of the produced water is by surface discharge (USGS, 2000).

The development of CBNG wells has increased rapidly in the PRB since 1997. In 1997 there were 360 CBNG wells with annual gas production of 14 MMCF. Since that time CBNG production in PRB has increased with the 2006 production level in the Wyoming portion of the basin alone amounting to more than 377 MMCF from 17,200 active wells. In addition to CBNG gas production, there is associated water production, which has also increased (www.bogc.dnrc.state.mt.us & www.wogcc.state.wy.us). CBNG development in the basin is expected to continue to grow. This development rate is likely to be closely linked to the availability of drilling rigs in the area, permitting processes, pipeline capacity, and the ability of CBNG operators to safely and economically manage the attendant volumes of produced water.

PRODUCED WATER MANAGEMENT

Produced water volumes associated with individual CBNG wells in the PRB show an exponential decline profile. Analyses that had been performed in both the Wyoming and Montana portions of the basin as part of the two Environmental Impact Statements (EIS) (BLM, 2003a, and 2003b) predicted that water rates would decline rapidly after the first few years. Depending on the estimated well life, average lifetime production rates were predicted to be between 2.5 and 4 gpm per well (ALL, 2001; BLM, 2001). Recent data from the Wyoming portion of the basin indicates average water production for active wells to be 3.5 gpm. The water volumes produced in the PRB per MCF produced are higher than in other CBNG areas in the US. (USGS, 2000).

The quality of CBNG produced water within the PRB varies across the basin. On the eastern basin margin where fresh water is recharging the coal seam aquifers, higher quality water is produced compared to areas in the basin's center. The water produced on the basin margin is often suitable for human consumption, livestock watering, and irrigation purposes. In the interior portions of the basin the CBNG produced water becomes unsuitable for human consumption or irrigation by traditional practices, yet is still of sufficient quality for livestock consumption. To successfully use the water for irrigation, a managed irrigation process is required with appropriate amendments.

CBNG operators in the PRB utilize a variety of water management options. Surface water discharge (via NPDES permits), managed land application, livestock watering, and infiltration impoundments are all being used to manage produced water. Additionally, several other water management strategies are being used, including industrial and beneficial use alternatives, such as dust control specific to coal mine operations; commercial fisheries; water recreation; recreational fisheries; aquifer storage/recovery; and others including injection. No one single water management solution exists and CBNG projects utilize a variety of water management solutions, but to-date there has been only limited use of re-injection as a water management option in the PRB for CBNG produced water.

RE-INJECTION OF CBNG PRODUCED WATER

Injection is dependant upon a number of variables, including, but not limited to the availability of a receiving formation(s), the quality of water being injected, the quality of water in the receiving formation, integrity of the confining zones, and the ultimate storage capacity of the receiving formation(s). These factors influence what type of injection well can be used as a tool for managing water produced in association with CBNG.

Injection is generally viewed as the emplacement of water into an aquifer or reservoir by pumping the water into an injection well that is completed in a zone or formation that is capable of receiving and storing water. Injection wells are regulated by the UIC program, which was initiated under the Safe Drinking Water Act (SDWA) to prevent contamination of underground sources of drinking water (USDWs). The UIC program, overseen by the EPA, allows states to have primary enforcement responsibility when the states promulgate regulations that meet the minimum standards set and approved by the EPA.

In the PRB, authority over the UIC program is shared between the EPA and the States of Montana and Wyoming. The Class V and other UIC programs other than Class II wells in the Montana portion of the PRB are under the control of EPA Region VIII. The MBOGC has primacy over the state's Class II UIC program, except on Indian Lands where the EPA has jurisdiction. In the Wyoming portion of the PRB the EPA in Region VIII directly implements the UIC program for all injection well classes on Indian Lands while the WOGCC and the WDEQ oversee the Class II and Class V programs, respectively.

In addition to this, Montana has an anti-degradation policy that further stresses the importance of groundwater in the state. The proximity of high-quality groundwater and oil and gas resources requires that proposed injection project applications include detailed groundwater quality analyses increasing the burden and cost to the overall permitting process and project.

It is assumed that any re-injection zone will be a coal seam within the Wasatch or Fort Union Formations that contains water less than 10,000 mg/L TDS and most likely contains water less than 3,000 mg/L. Class V wells are the only class of wells that can be utilized to inject into USDWs with less than 3,000 mg/L without a major UIC program revision. Because the feasibility of using wells other than Class V wells is believed to be minimal, it is assumed that the bulk of any re-injection would be done through the use of Class V injection wells. However, states and EPA could jointly determine through a major program modification to delegate the state's Class II UIC programs regulatory authority over this issue. As this modification has not occurred nor has it been initiated, the basic assumption of Class V being the most likely avenue for re-injection appears to be valid for the current regulatory environment.

The following presents the re-injection options and considerations that need to be accounted for when proposing any re-injection project. These considerations include technical, economic, and regulatory constraints that define the feasibility of re-injection as a viable water management option for any given CBNG project.

RE-INJECTION OPTIONS

The production of natural gas from CBNG wells requires a reduction in the hydrostatic pressure of the coal seam (Cox, 2001; Lamarre, 2001; Ayers, 2002). This reduction occurs through the production of water; therefore, in-field re-injection would almost certainly result in increased hydrostatic pressure, decreased gas production, and increased water production resulting in increased costs, and possibly a waste (or loss) of the natural gas resource. It would be against the interests of the CBNG operator to re-inject produced water into a productive CBNG field. Because of these technical considerations, the feasibility of re-injection into an actively producing coal seam is not currently considered a viable option. Re-injection ideally requires a depleted coal seam, an under-saturated (for water) non-productive coal seam, or an outcropping coal seam or clinker bed.

Coal seam re-injection has been represented as best occurring within a single active CBNG project (NPRC, 2001), but this process may also occur by producing and transporting water from one active CBNG project to another depleted project for disposal into a single, regionally extensive coal seam. Additional options that may fit into the re-injection concept would be injection into the same coal formation that is locally non-productive or where the coal does not have the hydrostatic pressure to trap methane, or when produced water is artificially linked with the ground water system allowing a groundwater discharge into a coal seam as part of shallow recharge project (potential using a modified infiltration system).

Re-injection into a depleted or under-saturated coal seam poses fewer technical concerns and is a more likely option. Once the productive life of a CBNG coal seam has ended, it may be feasible to convert production wells into recharge/re-injection wells. Depending on field testing results, it may be possible for converted wells to be used to inject water from other productive coal seams to restore the hydrostatic pressure within the depleted coal seams. In the PRB, CBNG fields typically use a singly-completed well to produce gas from a single coal seam while PRB fields often contain two or more coal seams that produce natural gas. In many cases, the stacked coal seams have very different production characteristics and different producing lives. In such a setting, one coal seam can be depleted long before the others in the project, and the depleted coal seam could become a target reservoir for re-injection.

Air Rotary Drilling LX Bar Creek Watershed, Wyoming

A consideration that should be accounted for when proposing to re-inject into a depleted CBNG seam is the potential of new enhanced recovery technology to increase the recovery of the natural gas. It has been estimated that the reserves recovered from a CBNG reservoir is approximately 50% (Cox, 2001), therefore approximately half the natural gas reserves are left in the coal seam after primary production. Enhanced recovery techniques such as CO_2 and N_2 injection are only lately being researched and considered. If an operator were to re-inject produced water back into the depleted zone, potential future enhanced recovery resources could be forever lost.

There is the possibility of injecting into a coal seam of the same producing formation that is locally non-productive. The coal seam used would need to meet the technical criteria defined below, as long as regulatory constraints permit the process. It should be noted that non-productive coal seams are often non-productive because the seam is not hydraulically isolated or the coal seam's isolation has been breached by fracturing, faulting, or erosion. The non-productive coal seam may be near the surface and possibly be in communication with surface water sources. Communication during re-injection could constitute an unpermitted release to surface water. In addition, the option of injection into a non-productive coal seam has inherent risks that could bring about additional regulatory and technical burdens as the non-productive zone could have a different classification of aquifer, leading to additional monitoring or reporting burdens on the operator.

Some have advocated treating CBNG produced water and re-injecting the concentrated brine residue into Class II disposal wells (NPRC 2004a, and 2004b). This practice would be a clear violation of current state and federal UIC regulations. The brine residues from treatment options such as Reverse Osmosis, freeze-thaw, Electrodialysis, and similar techniques have been determined not to be RCRA-exempt wastes and as such cannot be disposed in a Class II well. The brine residues are also from ten to 20 times as concentrated as the feedwater (BOR, 2003). For CBNG produced water, the resulting brine would be from approximately 15,000 to 30,000 mg/L or more; this water could not be re-injected into a coal seam containing formation water of 1,500 mg/L. Re-injection of the brine residue from CBNG water treatment plants into coal seams would be regulatorily impossible. Brine wastes are currently being managed as an industrial waste, which include disposal into Class I Non-hazardous injection wells that utilize deep, saline reservoirs.

To fully evaluate one of the above options for re-injection, modeling may need to be performed to assess the viability of the option. The costs of a full modeling study would also need to be incorporated into the overall project economics. Re-injection well placement can be modeled prior to drilling based upon site-specific values for CBNG reservoir pressure, injection zone reservoir pressure, permeability, storativity, and reservoir continuity. Without site-specific data, modeling would be subject to iterative revisions. In addition, changes to the physical parameters of the coal seam reservoir would need to be considered. These changes could make the modeling process difficult except in a sensitivity manner prior to actual field history matching being performed.

GEO-TECHNICAL CONSIDERATIONS FOR RE-INJECTION

Utilization of underground re-injection as a tool for managing produced water includes both technical and regulatory considerations. Technical issues may include such things as geologic, economic, and engineering factors. The evaluation of both engineering and economic considerations can vary significantly by operator and location; there are, however, a set of issues that must be considered relative to the hydrogeology of any proposed injection or re-injection well, including:

- ***Formation Suitability**:* Selection of a suitable re-injection zone/area within the producing formation may include several criteria, potentially including reservoir characteristics, depth, relative location to producing wells, other USDWs, potential discharges to rivers and streams, and springs. Suitability analyses for a proposed project would require the examination of local fracturing and faulting; the condition of active and abandoned wells within the area; and proximity of active and inactive coal mines.
- ***Isolation**:* The receiving formation must be vertically and laterally separated or otherwise confined from other USDWs. To be considered an appropriate injection zone, depleted coals should have exhibited isolation from adjacent coals during their production phase. In addition each injection well must also be equipped to isolate the receiving zone from other porous zones in the well to avoid unauthorized fluid movement into zones that are not permitted for injection.
- ***Porosity**:* Porosity is the percentage of void spaces or openings in a consolidated or unconsolidated material (EPA, 1991) Reservoir rocks are typically high in porosity, while confining zone rocks range from high to very low porosity. One major concern with CBNG formations is that the producing zones may compact during production. Compaction may depend on site-specific details such as the characteristics of cleat and joints in the field. Compaction could severely reduce porosity and permeability, making the depleted zones largely unsuitable for re-injection. Several authors have documented the tendency of coals to compact during de-gasification, leading to reductions in porosity and permeability (Palmer and Varizi, 2004). This process appears to involve the closing of cleat, the major pathways of coal permeability, as water and natural gas are produced. The loss of permeability may be irreversible but also may be prevented by the concomitant injection of CO_2 or other displacing gas during CBNG production. Such use of CO_2 injection early in the production phase may serve to preserve porosity and permeability. Compaction will vary from coal to coal and research will be needed to determine which coal seams offer the best opportunities for re-injection after depletion.
- ***Permeability**:* Permeability is defined as a measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient (EPA, 1975). A productive reservoir or an injection zone will have sufficiently high permeability to allow fluid movement. Confining zones which act as seals have very low permeability. Coals show a wide range of permeability due to porosity, cleat, and fracture distribution. CBNG production can cause irreversible compaction and loss of permeability.
- ***Storage Capacity**:* The storage capacity of a geologic unit can be estimated by estimating the pore volume of the entire injection zone. As an example, a 20 foot thick permeable interval that has 10% porosity is homogenous, and regionally extensive would have a storage capacity of 2 million barrels if the injected fluid extended for a radius of ¼ mile. With post-production compaction of the coal seam, the storage capacity of the CBNG zone would certainly be reduced.
- ***Reservoir Pressure**:* The reservoir pressure is the static pressure within the receiving formation expressed either as pressure (psi) or fluid head (feet). Reservoir pressure may limit the rate at which fluids can be injected and/or may limit the total injectable volume. Re-injection into depleted and compacted coal seams could involve higher injection pressures. Injection pressures may be so high that fractures could be initiated or augmented; fractures within and outside the injection zone could result in problems related to isolation.

- ***Water Quality:*** The quality and chemistry of the injected fluid and the formation water within the receiving formation may determine the type of injection well to be used. Since re-injection targets the return of produced water to the same formation it was produced from, this is not expected to be a factor unless the water is transported a distance and the receiving area has a different water chemistry than the producing area.

Variation of any of these technical considerations could cause the re-injection project to be unsuccessful, resulting in additional environmental concerns. A thorough understanding of the injection reservoir's characteristics and the water being managed is a necessity to make an injection project successful. Study and measurement of these characteristics is a necessity and can add cost to the overall management strategy.

ECONOMIC CONSIDERATIONS FOR RE-INJECTION

Re-injection of produced water is a viable and accepted alternative for managing water in conventional oil and gas operations. Its viability in the PRB for CBNG produced water continues to be evaluated on a case-by-case basis. Re-injection may not be feasible everywhere, largely dictated by economic conditions. Several important factors can influence the economics of re-injection including depth of the injection zone, injection pressures, transportation of the water, and regulatory burden. In addition, regardless of the re-injection alternative considered, the operator must be careful that correlative mineral rights are also respected.

- ***Depth of the Injection Zone:*** The major determinant in the cost of an injection well, whether a new drill or re-completion of an existing well, is the depth of the well. Actual costs vary from area to area depending upon drilling time, availability of suitable rigs, and other associated costs.
- ***Injection Pressure:*** The reservoir quality and pressure determines the required pumping pressures needed at the surface of the injection well. In some cases, the well may take water on a vacuum while in other areas, pumps are needed to overcome the lack of permeability and high residual pressures. Capital costs and operating costs need to be factored into the economic analysis.
- ***Transportation:*** Long-distance pipelining may needed to bring the water from the producing wells to the injection facility. These costs also need to be considered in the management plan.
- ***Regulatory Burden:*** Regulatory compliance consists of permitting and continued monitoring and reportage. Permitting costs will be directly dependent upon application complexity and agency review time. Complex forms will require a great deal of time to complete, extra analytical detail, and a long time for agency evaluation and approval. Class II permits are usually simple and easily approve but due to the necessity of a major program modification this could no longer be the case. Some Class V permits issued by the EPA can require more than 12 months for review and approval. Once permitted, the injection facility typically require monitoring and reportage at least at monthly intervals; in order to fulfill the requirements written into a permit, periodic laboratory analyses may also be required. These factors add to a site-specific cost-per-barrel figure that may be less than other available options, or may prove to be higher.

- ***PRB Unique Economics:*** Consideration should also be given to the fact that in the PRB the ratio of produced water volume to MCF is generally higher than in other CBNG basins (USGS, 2000). This adds an additional burden to facility/infrastructure costs, transportation costs, and the overall management of the produced water resource relative to the overall profitability of the project. Therefore, even minor increases to the per barrel management cost could result in significant deceases in the economic viability of a CBNG project in the PRB.
- ***Additional Costs and Liabilities:*** An additional cost that should be considered when evaluating a produced water management strategy is the relative costs in lost resources between differing methods. The added expenditure of energy resources to manage produced water for methods such as re-injection should be weighted against more energy efficient methods. In addition, if adjacent leases, whether producing or not, are impacted by re-injection, future economic liabilities may be involved.

REGULATORY CONSIDERATIONS FOR RE-INJECTION

In addition to the technical and economic considerations that must be accounted for to make a re-injection project feasible, additional regulatory considerations need to be considered;

- ***"Waste" Classification:*** As the produced water in the PRB is typically of high quality, it has been considered a resource not to be lost for future use through disposal. As the water is produced in association with the production of oil and gas, it could be injected into Class II wells, but this has been interpreted to be a waste of the resource by the WOGCC and is not permitted in Wyoming. For this reason re-injection of the resource for aquifer storage and recovery needs to be considered.
- ***Well Classification:*** Two types of injection wells are suitable for CBNG re-injection projects – Class II and Class V.
    - Class II injection wells can utilize USDWs if the formation water is greater than 3,000 mg/L for TDS. If the USDW contains water between 3,000 and 10,000 mg/L, an aquifer exemption will be required to demonstrate that the USDW will not be degraded.
    - To inject produced water into any other USDW, the injection well currently falls into the Class V category. The regulatory agency for Class V wells in Montana is the EPA and in Wyoming, the WDEQ. The potential to use infiltration (i.e., shallow wells installed in CBNG ponds that conduct pit water directly into shallow coal seam aquifers) injection wells to recharge USDWs that are non-productive or depleted CBNG zones has yet to be decided by the appropriate agencies. Even if these shallow wells are not equipped with pumps, they are UIC injection wells, requiring a valid UIC permit. This sort of uncontrolled injection may not be able to be permitted under the SDWA.
- ***Resource Conservation:*** Once the water has been produced and it is considered a resource, will the re-injection constitute a waste of the resource? As an example, if the producing CBNG horizon is at 4,000 ft. deep and the water is scheduled to be returned to that depth is this then a waste of the resource, as it may not be economic to ever return the produced water to the surface in the future?
- ***Water Rights:*** Once the water has been produced and it becomes a resource are there water rights issues and demands upon the volumes produced? Is it required by regulation to release the water for users that have prior appropriation water rights after the produced water has been classified as a resource?

- ***Correlative Rights**:* The process of re-injection may constitute an infringement upon correlative rights that may not be under development. Will the proposed re-injection plan impact CBNG production on these adjacent lands? Infringing upon the correlative rights of others based on an operator's water management could cause the operator to have liabilities to mineral rights holders for lost CBNG resources.
- ***Lost CBNG Resources**:* The re-injection of produced water and/or the recharge of CBNG aquifers through re-injection runs the risk of affecting the ultimate recovery of the producing horizon. This could result in litigation with resulting compensation to offsetting mineral interest holders. Regulators have to be conscious of these possibilities when permitting the use of re-injection as a water management option.
- ***Other Considerations**:* Due to the potential of compaction of a producing coal seam caused by the production of associated water, it may take more injection wells to inject an equal volume of produced water back into the coal than the number of producing wells originally drilled. Even if the operator was to wait until the seam was depleted and convert all existing producers this may not be a sufficient number of wells to re-inject all produced water. In addition, if additional wells were needed to be drilled, it would lead to increasing the footprint of wells in an area, thus increasing the environmental, regulatory, and economic impacts.

CONSTRAINTS ON CBNG RE-INJECTION

There are several constraints relating to the use of re-injection as a CBNG produced water management alternative, which include:

- ***Potential Impacts to CBNG Production**:* The CBNG producers want to maximize production to insure profitability but the producer also has an obligation under the lease agreement to the mineral owner to manage the CBNG resource in a responsible manner in order to return the maximum value to the mineral owner. Re-injection may jeopardize the performance of that obligation, making the operator liable for waste of the resource. In order to promote conservation of the CBNG resource, re-injection into zones geographically or stratigraphically close to producing coal seams will need to be monitored for pressure communication. Such a monitoring program will certainly add to production costs and may reduce the economically recoverable reserves.
- ***Post-Production Compaction**:* As noted CBNG production can cause irreversible compaction of the coal seam, making re-injection difficult or impossible. Only post-production injectivity testing can evaluate compaction.
- ***Re-Injection May Lead to Waste of Resources**:* Re-injection in close proximity to productive coal seams may result in a loss of CBNG resource. The loss would be a waste of valuable resources and may have repercussions beyond the loss of an injection zone. The owners of the wasted minerals as well as adjacent minerals may have cause to seek compensation from the operator for the waste of resources. In addition future enhanced recovery techniques may be developed that increase recoverable reserves; re-injection into the partly-depleted seam could ultimately hinder these recovery techniques.
- ***Permit Requirements**:* In order for the water management project to go forward, a number of agreements and permits will need to be in-place. Appropriate leases and damage agreements need to be negotiated with the surface and mineral owners to accommodate injection wells and pipelines. State, Tribal, and federal permits may also be necessary. Some injection permits, such

as general Class V CBNG permits, are currently available avenues; other regulatory processes to permit injection do not exist.

- ***Economic Loss of Resources**:* With the added costs of re-injection over other viable water management practices, there is the potential for lost resources due to making some CBNG resources not economically recoverable. Estimates of the economic impact of re-injection into coal seams as a CBNG water management approach suggested that the most optimistic scenario would result in a loss of 2 TCF of economically recoverable CBNG from the PRB (ARI, 2002). For the most conservative economic case presented, CBNG was not economically recoverable anywhere in the PRB if re-injection was the mandated water management option.

Re-injection has some specific issues that need to be addressed in order to be a feasible CBNG produced water management option. Additional research and field testing into these issues is necessary to assess the full potential of coal seam re-injection as an option in support of sustainable development of the CBNG resources in the PRB.

SUMMARY OF INJECTION OPTIONS FOR CBNG PRODUCED WATER IN THE POWDER RIVER BASIN

Class V Injection to Shallow Sands

Class V injection of CBNG produced water into a non-coal seam aquifer is a recognized technology in the PRB, although its widespread application has not been demonstrated. Such wells are typically categorized as aquifer recharge wells and aquifer storage wells.

Class V shallow injection include wells designed to place water into permeable horizons that exist within the coal sequences and into relatively shallow reservoirs which are generally located below the productive coal sequences.

Many coal-bearing formations in the PRB contain permeable sands that are hydrologically separated from adjacent zones by impermeable layers (De Lapp, 2005). Productive coal seams are often interbedded with sand beds forming a series of discontinuous lenses of coal and sand within the predominantly claystone sequence. The interbedded permeable layers can be hydrologically separated by either clay/shale zones or other such aquitards. When this condition occurs within the coal sequence the interbedded permeable horizons provide an opportunity for various types of injection, including disposal, aquifer storage/recovery, and possibly aquifer recharge.

Non-technical concerns and barriers to implementation related to the use of these Class V injection wells generally revolve around potential delays related to protests of permit applications. These protests may be related to technical merits of the applications including, but not limited to concerns raised by CBNG producers who fear negative impacts to existing CBNG production, which is productive in a nearby or adjacent coal seam.

The technical feasibility of Class V injection into shallow sands depends on the ability of the sands to accept water at a rate proportionate with the cost to construct and operate the well over time. Within the Wyoming portion of the PRB, approximately 150 Class V injection permits have been issued for CBNG water injection. Thirty-three wells were actually completed in shallow sands and used at least once while nine wells were completed in shallow coals (Likwartz, 2005). Of these wells, 16 were listed as successful by the operator and were used for up to three years. Of the 150 permits, 42 (approximately 25 percent) were completed, and 16 (approximately 10 percent) were considered successful. This included one situation where CBNG produced water was utilized to recharge a depleted municipal water supply source. In this example, the best injection well averaged over one million barrels per year for over three years (Olson, 2005).

In addition to the general technical concerns that apply to all injection operations the most common problem for Class V shallow injection wells is related to the loss of permeability over time. Permeability losses in shallow sands could be caused by plugging of reservoir pores with fines suspended in the produced water or by clay swelling (Olson, 2005). Careful pre-injection testing may be necessary to determine the sensitivity of the receiving formation to the produced waters and being injected.

Grouting Monitoring Wells in the Prairie Dog Creek Watershed, Wyoming

While data on volume capacity for shallow Class V injection wells is limited, data from the Wyoming portion of the basin suggests a range of between 500 and 4,000 bpd of CBNG produced water (Likwartz, 2005). A relatively modest sized CBNG project consisting of 100 producing wells generating an initial 150,000 barrel of produced water per day would require between 30 and 150 Class V shallow injection wells to meet the water handling requirement of the project. With an estimated success ratio of 25% for successful completions such a project would possibly require as many as 120 to 600 penetrations to establish the necessary Class V injection wells.

With respect to the economics of such wells, the amount of water each injection well can manage, the cost to drill and complete the well, the operating cost of the well, and the costs associated with non-successful injection wells will ultimately determine the economics of Class V shallow injection wells. Estimates of PRB per barrel costs for Class V shallow injection are extremely variable and range from less than \$0.10/bbl to over \$5.00/bbl (Likwartz, 2005). Installation expenses related to these wells, while also variable can easily exceed \$100,000 for the well and surface equipment. In addition to these capital cost there are also permitting, operating and regulatory reporting expenses. The most limiting economic parameters for this type of injection as an alternative for handling CBNG produced water are (1) the poor success ratio for wells drilled to date (25% in the Wyoming portion of the basin) and (2) the relatively low volume that an individual well has the capacity to accept.

Class V Injection into Coal Seams

Class V injection of CBNG produced water into coal seams is a produced water management option that has had extremely limited application in the PRB. Coal seam aquifers with some level of potential for handling such injection include shallow coal seams that are unconfined and open to the surface through surface recharge areas where the coal seam outcrops at surface and confined coal seams that are isolated from the surface by impermeable layers. The unconfined coal seams are generally not productive of CBGN and the lack of isolation from the surface area makes injection into such intervals highly problematic. The confined coal seams, on the other hand, are generally productive of both CBNG and water and are isolated. Confined coal seams with potential for use as re-injection intervals would include intervals determined not to be productive of CBNG or intervals that were productive but are now economically depleted. Injection into both of these types of confined coals seams has its own set of disadvantages and obstacles.

A depleted coal seam reservoir will probably have a lower reservoir pressure than when the reservoir began producing. If the reservoir pressure has been reduced, the reservoir may be able to accept large volumes of fluid at relatively low injection pressures. Research, however, has indicated that methane productive coals can compact as they are produced. Observed permeability reductions 600 times lower than those noted during production have been attributed to such compaction and other rock factors (Mazumder et al., 2003).

These reductions in permeability and porosity during compaction would have the tendency to increase injection pressure and decrease injection rate if the depleted coal seam was targeted as an injection candidate. It is unknown whether these compaction effects will occur to the same degree in PRB coals but if they do, these factors would severely limit the usefulness of depleted coal seams as injection zones.

A coal seam that is depleted in one CBNG project may still be productive in an adjacent CBNG project. If an application was filed for a Class V injection permit in a depleted well or project, that application may be protested by an offsetting producer fearing that any injection could negatively impact adjacent production. In the case where the adjacent minerals are not leased, the mineral owner would have the same opportunity to protest the Class V injection well application on the basis of potential for damage to the reservoir and impact to correlative rights. The opportunity and likelihood for offset operators and mineral rights owners protesting virtually any re-injection application makes re-injection into depleted coal seams a high risk alternative (Likwartz, 2005).

In addition to the concern relative to impacts to offsetting production and correlative rights, another barrier to the use of depleted coal seams would include the loss of possible future economic reserves from the coal seam. Currently, production techniques are estimated to recover only approximately 50 percent of the gas-in-place, leaving the remainder of the gas still absorbed to the coal and dissolved in the pore water. Injection into the coal seam would re-saturate the zone and those coal seams would be lost for potential enhanced gas recovery opportunities that may be developed in the future.

Technical parameters that will influence the use of coal seams as injection targets include permeability, porosity, and injectivity. The coals productive of CBNG in the PRB to date are able to produce water at rates in the range of 500 to 1,000 bpd during the initial phase of production. This apparent excellent permeability is a function of the coal's pore system, local fractures, and its cleat system. A coal's cleat can be explained as a system of fine-scale fractures that are largely the result of the dewatering process in which organic peat is diageneticaly transformed to coal. As this cleat system is de-pressurized by desorption and production of the CBNG, it collapses and the coal loses permeability. Because of this lost permeability depleted coal seams can only accept a small portion of the water withdrawn during production.

While this loss of cleat permeability is an important factor in predicting the ability of a depleted coal seam to accept injected fluids it appears to be of less importance in non-productive or unconfined coal seams. These shallow non-productive or unconfined coals also appear to have higher matrix porosities. However, as noted the higher potential for surface discharge related to the lack of sufficient isolation makes injection into such unconfined intervals problematic.

Environmental concerns for injection into coal seams are generally related to injection into non-productive or unconfined coal seams. Again the primary concern is related to the potential risk of breakout of the water to the surface in nearby springs and under nearby streams or rivers (Wagner, 2005). Additional ancillary concerns are related to the potential for leaching of minerals and salts and the subsequent transport of these constituents to surface waters.

Injection into coal seams in the PRB is at this time is extremely limited. Historical records from nine wells that injected into shallow non-productive coal seams in the Wyoming portion of the basin show injection rates from less than 100 bpd to more than 2,000 bpd. Those wells were completed at depths between 45 to 400 feet bls. A more recent shallow test well completion in a non-productive dry coal seam in the Montana portion of the basin was tested for permeability and injection rate by way of an injection and fall-off test. That test measured permeability at 1.1 darcy and indicated a maximum injection rate of slightly more than 10,000 bbls per day (Pinnacle Gas Resources, 2007). However, no volume data is available for actual sustainable input rates, which would be below the maximum test rate. Potential volume capability for most coal seam injection wells would most likely fall within the range of the data currently available, which indicates a rate 100 to 2,000 bpd. Under such a range of injection rates a 100-well CBNG project producing 150,000 bpd of water would require between 75 to 1,500 coal seam injection wells to successfully handle the initial produced water output for the project.

The economics of re-injection into shallow coal seams as an option for produced water management is difficult to accurately forecast depending on a number of factors. Estimates of per barrel costs may be in the same order of costs estimated for Class V shallow injection wells which is estimated to range from $0.10 to more than $5.00 per bbl. Transportation costs for injection into depleted coal seams are likely to be high in many areas of the PRB if proximity to on-going production is to be avoided along with the associated probable protests such applications would draw.

Class II Injection (Class IID and Class IIR)

Injections wells that are typically used for conventional oil and gas injection operations have the potential to be used to handle CBNG produced water. Deep injection wells used for injection as part of oil operations below any USDW are classified as Class II wells by the EPA. Class II injection wells are further subdivided as either disposal wells (Class IID) or enhanced recovery wells (Class IIR)

Class II disposal permits may be issued for injection into underground reservoirs that have greater than 10,000 mg/L TDS or are an exempted aquifer. Deep aquifers that are suitable for injection but contain less than 10,000 mg/L TDS require an aquifer exemption in order to receive a Class IID permit. Such aquifer exemptions are provided for under regulations to avoid giving full protection to low quality aquifers that will never be used for public water supply. While applications for exemptions require specific information relative to the target horizon, generally aquifers found at depths greater than 10,000 feet would be likely candidates for such exemptions as it is unlikely that such an aquifer would be an economic source for a public water supply. Likewise, an aquifer with over 10 ppm oil and grease or over 5,000 mg/L TDS would be difficult to portray as a source of drinking water (WDEQ, 2005). Such conditions might include several formations within the PRB with the most probable target being the Madison Formation. The Madison Formation is a thick carbonate with good porosity underlying much of the PRB and would be capable of handling a large volume of fluid. The depth to the top of the formation ranges from approximately 8,000 feet at the edges of the basin to more than 14,000 feet at the basin axis.

Permitted Class II enhanced recovery wells (Class IIR) are put in place to more efficiently produce oil from certain conventional oil fields. Either existing producing wells or newly drilled wells are fitted for injection of water in an effort maintain reservoir energy and drive more oil toward the producing wells.

The water injected into Class IIR wells can be water produced from the field being water-flooded or it can be “make up” water obtained from another source. As the water-flood progresses, the target reservoir fills up and eventually the injected water and additional oil will be seen at the producing wells. As production continues, the water produced in the oil wells replaces the make-up water and the flood becomes more or less self-sustaining and no outside water is needed. The size of such enhanced recovery injection operations may be as small as a few wells to as many as several hundred wells with fluid requirements for makeup water within a range of from less than 1,000 bpd to more than 50,000 bpd.

Deep Class IID wells are commonly able to inject large volumes of water. These wells are inherently safe, as the injection zones are generally very deep and isolated by thick, impermeable confining zones safely confining the injected fluid away from drinking water aquifers. Class IIR wells which have comparable construction requirement to Class IID wells are similarly isolated from fresh water aquifers. These wells can be capable of receiving good volumes of make up water from sources outside of the existing oil field in which the injection is taking place.

While Class IID injection for oil field waters is a proven well established technology with a very good environmental record. Class II disposal is not widely used in the PRB because of the depths and associated costs required to reach the appropriate target horizons and the sporadic nature of the effective reservoir development. Estimated costs for such wells for use in handling CBNG produced water would likely be in the order of $4 million to $5 million dollars for drilling and completion of the necessary 10,000 to 14,000 foot wells. The economics of this water management option for CBNG is difficult to predict, but is probably in the order of conventional Class II disposal which ranges from $0.10 to $1.00 per barrel.

Monitoring Well Development in the Prairie Dog Creek Watershed, Wyoming

Well construction costs for Class IIR wells for use in handling CBNG produced water would likely be comparable to conventional waterflood wells and would again depend on well depth. However, transportation costs of delivering the water to the targeted waterflood operation may be substantial and would likely affect the overall economics of this alternative. Pipelines needed to transport the CBNG water would cost approximately $43,000 per inch-mile which would necessitate careful matching of CBNG produced water source areas with possible waterflood opportunities to maximize the economics of such an alternative for CBNG water management. Operating costs beyond pipeline and pumping expenses would be most likely consistent with conventional waterflood operational costs which are generally less than $0.10 per barrel.

CONCLUSIONS

The re-injection options listed identify a number of ways re-injection into coal seams might be utilized as a CBNG produced water management option. Like most water management strategies, these options have both advantages and disadvantages. In most cases, the disadvantages are less well understood and carry a risk of high operating costs and the potential for future liabilities.

Re-injection in an on-going producing area is counter-productive to the process of de-watering the reservoir and lowering reservoir pressure which is critical for developing CBNG. At the same time, the production of CBNG can result in the compaction of individual coal seams to such an extent that any subsequent water re-injection would be restricted or even prevented. The use of a depleted coal seam reservoir for re-injection would certainly require planning and the construction of an extensive operational support system. Re-injection would necessarily lie in the future of any CBNG project as re-injection would not be a viable option during the early peak water production periods that occur during the initial stages of production. Thus any early-stage re-injection would require an extensive and costly transportation network to move the produced water to a depleted CBNG field.

Technical, regulatory, and economic conditions may mean that the use of re-injection could cause water or natural gas resources to be lost and unrecoverable. Future technologies which hold promise for increasing the recoverable reserves of CBNG reservoirs are untested and re-injection could prevent the future use of such techniques and thus diminish the ultimate recovery of a CBNG field. Such reductions in recovery could leave the CBNG operator open to future liabilities to the mineral owners for lost reserves. Regulatory considerations may require a major program modification to classify coal seam re-injection wells under the Class II UIC program so that injection into an aquifer can occur.

Based on the shear number of technical considerations that have yet to be thoroughly evaluated, it is unknown to what extent re-injection options may be used in water management strategies for the PRB. A 2002 report prepared for US DOE ARI noted that “shallow re-injection is a high risk option and may be considered a speculative alternative at this time.” As coal seam re-injection still remains relatively untested under field conditions and has not as of yet thoroughly examined by the relevant regulatory agencies, it may take some time before the feasibility of these options can be accurately determined.

Finally, current water management practices in the PRB comprise a variety of alternatives or options that are implemented on a site-specific basis. To date no single practice has become a standard within the basin or even a large portion of the basin. Coal seam re-injection as a water management strategy still requires continued research and field testing before it can become a viable or widespread management option.

THIS PAGE INTENTIONALLY LEFT BLANK

SURFACE WATER AND GROUNDWATER RESOURCES OF THE POWDER RIVER BASIN AND IMPLICATIONS FOR CBNG DEVELOPMENT SUMMARY

INTRODUCTION

This section of the report presents information on surface water and groundwater, water uses and water statistics that relate to CBNG development activities within the PRB of Wyoming and Montana. The PRB is a fossil-fuel producing basin with historic conventional oil and natural gas production dating back to the early 20th century, coal mining dating back to the 19th century, and CBNG production expanding since the early 1990's. In addition to fossil energy production, the PRB has been a ranching and farming area where livestock have been grazed and limited crops harvested since the area was first settled by European immigrants. With the expansion of fossil energy production within the PRB in recent years, there have been concerns that the quantity and quality of surface water and groundwater resources in the PRB may be affected. Recent EISs performed by BLM introduced the possibility of impacts to water resources of the PRB. This report updates the EIS analyses and reassesses the possibilities for impact to groundwater and surface water in the PRB.

BACKGROUND ON THE POWDER RIVER BASIN

The Powder River Basin is located in southeastern Montana and northeastern Wyoming. The PRB encompasses approximately 21,850 Square Miles or 14.0 Million Acres; an area the approximate equivalent of the states Vermont, New Hampshire and Rhode Island combined. The PRB encompasses portions of seven counties in Montana (42.7% of the total area), eight counties in Wyoming (57.3% of the total), portions of two Tribal Lands (the Northern Cheyenne and the Crow), and Federal Lands managed by both the Bureau of Land Management (BLM) and the U.S. Forest Service. The majority of the PRB is pastureland used for grazing of livestock (80%), while other land uses include some crop production, recreational use, and fossil energy production. Agricultural production comprises the largest land use activities, with grazing lands utilizing the largest acreage, approximately 11.2 million acres of the 14.0 million acres, while only 266,500 acres or 1.9% is irrigated crop land (USDA, 2005). Additionally, private and federally managed land is also being utilized for the extraction of coal, oil, and natural gas to meet national energy needs.

WATER RESOURCES IN THE POWDER RIVER BASIN

Water resources within the basin as a whole consist of surface water bodies, groundwater resources from a variety of geologic formations including surficial alluvial aquifers, coal seam aquifers, and precipitation which acts to recharge the aquifers and supplies the surface waters. The climate of the PRB is semi-arid to arid with rainfall averaging approximately 14 inches per year across the basin. The arid conditions result in highly variable flow rates in streams of the PRB and seasonal fluctuations in the groundwater levels of the shallow alluvial aquifers. All surface water bodies from major watersheds to include the Powder, Tongue, and Big Horn Rivers eventually discharge into the Missouri River.

CURRENT CBNG DEVELOPMENT IN THE POWDER RIVER BASIN

The extraction of CBNG in the PRB first started being tracked around 1987; at that time there were seven producing CBNG wells in all of the PRB. CBNG production slowly increased until about 1997 when there were 360 wells and the annual gas production was 14 MMcf. Since 1997, CBNG production in PRB has increased and currently the PRB is the fastest growing CBNG basin in the United States with 12,465 wells producing 353 MMcf in the year 2003. Because of the rapid expansion of CBNG production in the PRB and the fact that much of the coal minerals are federally managed, the Wyoming and Montana BLM prepared EIS's to assess the impacts of the Reasonable Foreseeable Development (RFD) of CBNG in the PRB of Wyoming and Montana. Although the exploration and production of CBNG has increased since the Final EIS's were issued in January 2003, the rate of development has not matched the rates foreseen in the RFD scenarios.

WATER FACTS AND STATS FOR THE POWDER RIVER BASIN

The three largest watersheds in the PRB, the Cheyenne, Powder and Tongue Rivers, cover more than 65% of the total area in the PRB and have the greatest total stream length at 5,407 miles, 7,920 miles, and 6,391 miles, respectively. The three smallest watersheds, the Bighorn, North Platte, and Upper Little Missouri Rivers, cover for less than 5% of the total area and have a combined total stream length that is less than the next smallest watershed, the Belle Fourche River. Five surface watersheds (Little Powder, Belle Fourche, Upper Little Missouri, Lower Yellowstone-Sunday and Cheyenne) have main-stem rivers that are head-watered inside the basin boundary, and three other watersheds (the Tongue, Big Horn, and Powder) have main-stems that are head-watered in the Big Horn Mountains outside the western boundary of the basin.

Precipitation in the form of rainfall and snow melt is one source of surface water flows in these watersheds and contributes to the recharge of groundwater in the shallow alluvial aquifers which are associated with these streams and their tributaries. The average precipitation across the PRB is approximately 1.1 foot of water, a volume equal to 656 million cubic feet of water per year. The United States average is nearly 3 times this amount with the average for the entire U.S. being approximately 30 inches of precipitation per year (EPA, 2002). Most of the precipitation in the PRB is lost to evaporation and plant transpiration. In the PRB, average annual lake evaporation values are 5 to 6 times (50 to 60 inches/yr) greater than the precipitation rates (NOAA, 2004).

Air Rotary Cuttings of Silts for the Wasatch Formation, LX Bar Creek Watershed, Wyoming

The peak flows in the PRB watersheds typically occur in the spring when the snow pack in the western mountains and within the basin melts; this water then flows overland and eventually discharges into the surface streams. River and stream flows within the watersheds of the PRB are highly variable and have a bimodal flow pattern. For most of the PRB watersheds there are two distinct peak-flow episodes; only the Tongue River station fails to show the two distinct flow peaks during the average year. The Belle Fourche and Little Powder Rivers have their largest peak-flows earlier in the year than the Tongue or Powder Rivers, with a peak around March when temperatures inside the PRB, where these rivers originate, climbs high enough to melt snow. Both the Tongue and Powder Rivers have peak flow values during June when temperatures in the mountains, where these streams originate, cause the snow pack to melt and flow into these surface streams.

Surface water quality in the PRB typically has an inverse relationship with flow in these watersheds. This inverse relationship is a result of high flow volumes during the spring, having water that is generally higher quality than during base flow periods. The reason for this is the source of the water being significantly different during these times with rain fall and snow melt water being of higher quality than the water that is discharged from the alluvial aquifers in base-flow. The surface water in the Tongue River is typically much higher quality than other watersheds in the PRB, with average EC values below 800 µsiemens/cm; however, the quality and quantity relationship evidenced in the Tongue watershed is similar to the relationship identified in the other watersheds. The current drought is exacerbating this relationship since the reduced flows and lower groundwater levels have resulted in less recharge of the alluvium and longer residence time for the water in the alluvium. These two factors combine to result in the reduction of the quality of the groundwater in the alluvium which infiltrates into the streams during base flow time periods.

Surface water use in the PRB is dominated by irrigation withdrawals with over 85% of the total surface water withdrawn being used for irrigation. The next two largest withdrawals (mining water and public water supply) account for most of the remaining 2% of surface water withdrawals in the basin. As was previously noted only 1.9% of the land within the PRB is irrigated, but this activity accounts for the largest surface water withdrawal. Irrigation from the Tongue and Powder Watersheds account for 77% of the irrigated acreage and 80% of the irrigations withdrawals. Irrigation withdrawals represent the removal of nearly 6.5% of the average annual precipitation within the PRB.

Groundwater

Groundwater in the PRB is predominantly extracted from two sources, shallow alluvial aquifers near the surface water streams and coal seam aquifers. According to the USGS water use study for 2000 and the incorporation of CBNG water production data from the WOGCC, approximately 57.5 million gallons of groundwater are extracted from the PRB per day (USGS, 2001; WOGCC, 2004). The two largest withdrawals of groundwater in 2000 were energy related activities, CBNG production and mine water use (both fresh and saline) which account for a total 90% of the groundwater use.

Aquifers

Groundwater can be found in several aquifers within the PRB. Five major groups of aquifers are especially important to ranchers and other residents of the basin: Alluvium, Tertiary Coal Wasatch, Upper Cretaceous Sands, Lower Cretaceous Sands and Paleozoic Aquifers.

Alluvial Aquifers

Virtually all stream and rivers within the PRB include alluvial valley fill of varying with and depth; many water wells produce water from this alluvium for domestic and farm use. The water quality of alluvial aquifers in the PRB is dependent upon the mineralogy of the bedrock and the quality of the water in the surface streams. Alluvial groundwater may have connection with coal seams or deeper aquifers. Many of the bedrock aquifers outcrop in the basin or at its margin; in these outcrop areas alluvium may be in close connection, allowing alluvial groundwater to mix with other aquifers.

Coal Seam Aquifers

Groundwater quality within the various producing coal zones varies considerably and is primarily based on the specific chemistry of the differing coal zones. Water quality parameters for coals in the Fort Union Formation are generally higher than for coals from the Wasatch formation with the exception of calcium and magnesium. The lower median concentrations for calcium and magnesium within the Fort Union Formation, combined with a higher median concentration of sodium, combine to give a higher Sodium Adsorption Ratio (SAR) value for the Fort Union.

Deep Aquifers

The Powder River Basin is primarily filled with Tertiary aged, mixed lithology strata having very few clean sands with good porosity and permeability. The Tertiary basin fill rests upon the Western Great Plains sequence of Paleozoic through Cretaceous sediments, which includes both aquitards and aquifers. Throughout the PRB, as the aquifers get deeper, there are fewer water wells completed into them. The Lower Cretaceous and Paleozoic aquifers support few wells within the basin. Water quality varies across the basin in the deep aquifers.

THIS PAGE INTENTIONALLY LEFT BLANK

ANALYSIS OF SURFACE WATER QUALITY AND QUALITY IN THE WATERSHEDS OF THE POWDER RIVER BASIN

INTRODUCTION

This report evaluates five watersheds and includes the Tongue River (via the USGS's Decker, Montana station 06306300), the Powder River (via the Arvada, Wyoming station 06317000), the Little Powder River (via the Weston, Montana station 06324970), Cheyenne River (via Antelope Creek near Tekla, station 06364700 and the Cheyenne near Dull Center, station 06365900), and the Belle Fourche River (via the Moorcroft, Wyoming station 06426500). These are the five watersheds that have experienced CBNG development including produced water discharge and other management techniques. CBNG development and water management practices have occurred in these watersheds since 1993; most watersheds however had limited CBNG production activity until about 1999. The effect that CBNG development can have on surface water is a concern for irrigators, who are the primary water users of surface water within the PRB, as well as other users.

Statistical analysis was performed on the historical record of Flow, EC, and SAR values for pre- and post-CBNG development for the five gauging stations previously mentioned.

CHEYENNE RIVER WATERSHED SURFACE WATER PARAMETERS

The Cheyenne River has only scattered stream flow and water quality data; not sufficient for comparing pre-CBNG and post-CBNG conditions. One of its tributaries – Antelope Creek – does have some data and has CBNG development in its upstream reaches. This stream is one of a few that displays a multi-peak flow prior to the drought; the March peak is likely due to snow-melt runoff while the May and August peaks are likely due to summer rain events. Prior to the drought, the annual average flow in the Antelope was 6.13 cfs but during the drought, the average has dropped to 0.88 cfs. Discharge of CBNG produced water does not appear to be impacting the Antelope at the gauging station since the average flow has been less in the post-CBNG era for every month except July. Pre-CBNG base-flow is much the same as high-flow water quality, which may be due to the spread-out nature of the high-flow period. Post-CBNG base-flow, however, is worse than high-flow; this could be entirely due to the strong drought effect.

The Cheyenne River watershed has 1,028 active CBNG wells, 223 permitted CBNG impoundments, and no permitted CBNG water discharge points as of October 2002. For 2003 (the last complete year of records) 25.6 Bcf of CBNG were produced and 25.8 Million bbls of water were produced at the same time (WOGCC, 2004). The Cheyenne River, as gauged near Dull Center, averaged 56.54 cfs during the pre-CBNG years for an annual volume of approximately 318 Million bbls. No post-CBNG gauging has been done on the Cheyenne. However, if the same ratio that Antelope Creek showed in the pre and post-drought stream flow is used, the drought-corrected Cheyenne River flow would be 45.65 Million Bbls per year.

BELLE FOURCHE RIVER WATERSHED SURFACE WATER PARAMETERS

The Belle Fourche was affected by the recent prolonged drought as have other watersheds in the basin; pre-drought flows averaged 55.70 cfs while drought flows have averaged 24.10 cfs, a 57% reduction. The Belle Fourche watershed has 5,085 active CBNG wells, 227 permitted CBNG impoundments, and 15 permitted CBNG water discharge points. For 2003 (the last complete year of records) 149,700,000 mcf of CBNG were produced and 210,733,061 bbls of water were produced at the same time (WOGCC, 2004). The river averaged 52.6. cfs during the post-CBNG years for an annual volume of approximately 295 Million bbls. During 2002, approximately 1.9 Million bbls of produced water was discharged according to the Wyoming State DEQ.

The Belle Fourche watershed average monthly flow data shows that a shift in the peak discharge for the river occurred between the sampling records for pre- and post-CBNG data sets. The pre-CBNG mean monthly flows peaked in March with a mean flow value of 256 cfs while the post-CBNG mean flow value peaks in June with a value of approximately 290 cfs. The largest monthly percent difference occurs during October when the monthly average flow increased by 1,039% during the post-CBNG years. The largest decrease in percent difference is observed in February where the post-CBNG flow was 84% lower than pre-CBNG flow. For eight of the twelve months, the post CBNG values show an increase in the average monthly flow. The average annual flow results in an increased average annual flow for the Belle Fourche River watershed of approximately 15% which equates to an average annual flow of 52.6 cfs in the post-CBNG time period compared to a pre-CBNG average annual flow of 45.8 cfs.

The post-CBNG development years show no months in which the river ran dry, and only two months (January and July) in which the minimum flows fell below 1 cfs. However, the maximum recorded flow values show that pre-CBNG flow was greater (2,400 cfs) than the post-CBNG maximum recorded flow (1,490 cfs). The changes in the flow data could reflect long-term climate effects or CBNG discharge effects; in either case the main difference is the increased flow during May and June of the post-CBNG period.

Both EC and SAR parameters show mixed trends with increases and decreases in the post-CBNG values when compared to the pre-CBNG values. The majority of the pre-CBM average monthly EC and SAR values are indeed higher than post-CBM values, with nine monthly values being higher for pre-CBNG EC values and ten pre-CBNG SAR average values. The yearly average values show a 7% decrease in the post-CBNG EC and a 15% decrease in the post-CBNG SAR. In general, water quality data reflects an overall improvement in surface water quality since the start of CBNG development in the Belle Fourche watershed. This trend is especially evident during May and June when the post-CBNG flow rates were highest; the additional flow was clearly higher quality water, most likely meteoric water. The exception to this trend is the summer period from July into September when pre-CBNG values were less for both EC (post-CBNG increases of between 4% and 29%) and SAR (post-CBNG increases of between 11% and 16%).

LITTLE POWDER RIVER WATERSHED SURFACE WATER PARAMETERS

The Little Powder watershed holds 2,108 active CBNG wells, 220 permitted CBNG impoundments, and 91 permitted CBNG water discharge points as of June 2002. For 2003 (the last complete year of records) 38,600,000 mcf of CBNG were produced and 66,300,000 bbls of water were produced at the same time (WOGCC, 2004). During the post-CBNG era, flow in the Little Powder has averaged 20.56 cfs for an annual total volume of approximately 115 Million bbls of water. The average monthly flow data for the Little Powder Watershed shows a considerable decrease in flow occurred between the pre-CBNG years and the post-CBNG years for the months with the greatest pre-CBNG flows. The overall decrease in post-CBNG flow is most likely the result of the severe drought the PRB has been experiencing; evidence to support this can be seen in the maximum monthly flow values observed for the post-CBNG. The drought essentially erased the presence of any high-flow regime; the Little Powder is now in base-flow throughout the year, on average. Other causes for reduced flow rates at the Weston stream gauge could be increased withdrawals for irrigation or mine usage.

Both EC and SAR parameters show mixed trends with increases and decreases in the post-CBNG values when compared to the pre-CBNG values. The post-CBNG average monthly EC values show evidence of the drought effect that was previously postulated. For seven months the post-CBNG EC values are greater than pre-CBNG values with the increases ranging from 8% in October to 60% in August. For the five months where the EC values are less in the post-CBNG time period, the decreases range from 4% in November to 31% in January. The annual average EC values show a net increase of 2% in the post-CBNG time period, which is equal to a net change of 53 µsiemens/cm. The average monthly SAR values show an increase in the SAR for the post-CBNG values during nine months ranging from 2% in July to 34% in August. For the three months of the post-CBNG data that show a decrease in SAR values, the change ranges from 9% in December to 25% in January. The increases observed for the post-CBNG average monthly EC and SAR values appear to correspond in most instances to decreases in the average monthly flows.

POWDER RIVER WATERSHED SURFACE WATER PARAMETERS

The Powder River watershed holds 4,057 active CBNG wells, 1,141 permitted CBNG impoundments, and 273 permitted CBNG water discharge points. For 2003 (the last complete year of records) 19,700,000 mcf of CBNG were produced and 38,500,000 bbls of water were produced at the same time (WOGCC, 2004). During the post-CBNG era the Powder Watershed has an average flow of 153 cfs for an annual volume of 859 Million bbls of water. The average monthly flow data for the Powder Watershed shows a considerable decrease in flow occurred between the pre-CBNG years and the post-CBNG years for the months with the greatest pre-CBNG flows. Average monthly flow values for all but July (increased 43%) and December (no change) have decreased from the pre- to post-CBNG development data sets. The average monthly flow values vary in the degree to which they have decreased with the lowest being January at 9% change and the largest being May with a 91% change. The average yearly flow decreased substantially from 486 cfs to 153 cfs, a 69% decrease.

Further evidence of the change in monthly flows can be seen in the observed minimum monthly and maximum monthly flows, with the pre-CBNG minimum flow of 0.00 cfs occurring in the month of September, while the post-CBNG minimum monthly flow of 0.00 cfs occurred in the months of August, September and October. The maximum monthly flow observed for the pre-CBNG flows was 17,800 cfs recorded in May; the post-CBNG maximum was only 2,260 cfs.

Both EC and SAR parameters show mixed trends with both increases and decreases, but no change in the annual average in the post-CBNG values when compared to the pre-CBNG values. Seven months of post-CBNG average monthly EC data show decreased values compared to pre-CBNG data, with a range from 6% in April to 19% in January. Five months of post-CBNG average monthly EC data show increases ranging from 2% in September to 34% in June compared to the pre-CBNG data. The range of minimum to maximum EC monthly values is greater during the pre-CBNG data with values ranging from 70 µs/cm to 6,500 µs/cm. Post-CBNG EC data has a range from 1,330 µs/cm to 5,170 µs/cm.

Changes that have occurred to the water quality in the Powder River Watershed, as reflected by SAR and EC values, appear to be a combination of several contributing factors. The first is an inflow of groundwater from the shallow alluvial aquifers in the form of base-flow, resulting in the SAR and EC increases observed from May to August. In addition, from September into February there appears to be an influx of slightly higher quality water that has reduced EC and SAR values in the post-CBNG data. This higher quality water may be attributable to CBNG produced water discharges which can be higher quality water than that present in base flow.

TONGUE RIVER WATERSHED SURFACE WATER PARAMETERS

The Tongue Watershed holds 2,230 active CBNG wells, 170 permitted CBNG impoundments, and 20 permitted CBNG water discharge points. For 2003 (the last complete year of records) 35,600,000 mcf of CBNG were produced and 65,300,000 bbls of water were produced at the same time (WOGCC, 2004; and MBOGC, 2004). During the post-CBNG era the Tongue River average flow was 265 cfs for a total annual volume of 1,488 Million bbls. Total annual CBNG discharge into the Tongue River for 2002 (last complete year of data) was 51.36 Million bbls.

The average monthly flow data for the Tongue Watershed shows a considerable decrease in flow between the pre-CBNG years and the post-CBNG years. Although the high-flow period remains the same (May and June), average monthly flow for all months have decreased from pre- to post-CBNG development ranging from 19% in July to 74% in August. The average yearly flow decreased 42% from 454 cfs in the pre-CBNG data to 265 cfs in the post-CBNG era. The almost uniform and consistent reduction in average monthly flow would be consistent with widespread drought conditions.

EC average monthly values show mixed trends with increases and decreases in the post-CBNG values when compared to the pre-CBNG values. EC values have increased for eight months ranging from 3% in July to 38% in September. Four months have shown small decreases in EC in the post-CBNG era ranging from 2% in February and December to 13% in March. The Tongue Watershed shows more clearly the initial base-flow period (August and September) increases in EC for the post-CBNG era. Other base-flow months, such as December and February, show smaller decreases in average monthly EC values. The overall post-CBNG yearly average EC value shows only an 8% increase when compared to the pre-CBNG yearly average EC value.

SAR average monthly values show a more distinct increase in the post-CBNG values when compared to the pre-CBNG values for the Tongue River Watershed than was seen in the other watersheds in this study. For those months in which pre-CBNG SAR data was available for comparison (all months but March and April), the data shows increases in post-CBNG data with percent differences ranging from 12% for December to 153% for September. The SAR data for the Tongue Watershed documents the correlation between the lower flows in the post-CBNG period and the decreased water quality, which would be expected during a severe drought such as the PRB is currently experiencing.

SURFACE WATER NUTRIENT LOADS – POWDER RIVER

Analysis of Sulfate, Chloride and Nitrate concentrations in the Powder River were developed to determine the mass of these nutrients that are being moved through the system on an annual basis. Data from the USGS Powder River at Moorehead surface water monitoring site was used to determine the mass in Kg/year that is moved through this site location over the course of a year. The analysis was performed for the last three years of complete data available (2005, 2006, and 2007). For the year 2005, the total nutrient loads were 128, 900,000 Kg/year for Sulfate; 22,800,000 Kg/year for Chloride, and 48,100 Kg/year for Nitrate. For the year 2006, the total nutrient loads were 82,500,000 Kg/year for Sulfate; 15,600,000 Kg/year for Chloride, and 56,000 Kg/year for Nitrate. For the year 2007, the total nutrient loads were 235,200,000 Kg/year for Sulfate; 36,800,000 Kg/year for Chloride, and 222,000 Kg/year for Nitrate.

GROUNDWATER ANALYSIS – POWDER RIVER BASIN

Wyoming CBNG Produced Water

The groundwater model for the Wyoming portion of the PRB (BLM, 2002) was developed to provide predictions for years 2003, 2006, 2009, 2012, 2015, and 2018. Model projections for the quantity of CBNG water are fully 231% higher than actual water production for year 2002, 285% higher for year 2003, and 359% higher for 2004 (extrapolated). Lower actual groundwater production volumes versus predicted volumes would suggest that much lower drawdown of actual groundwater levels have occurred than those predicted in the model. The quantity of CBNG water produced for year 2003 is actually 2% less than the amount produced for 2002 rather than the 21% increase projected by the model. CBNG water production for the first four months of 2004 is also 10% lower than the corresponding first four months of 2003.

Data shows that, while the number of CBNG producing wells have generally increased the quantity of produced water, while varying somewhat, overall production has generally been on a decline. The typical scenario for water production from a single CBNG well is high initial water production of 10 to 20 gpm decreasing over time to a lower steady-state production of 1-10 gpm. One of the likely causes for the observed lower water production volume is that individual wells are showing greater well interference along with more efficient de-pressurization of the coal seams, therefore producing wells are reaching the lower steady-state of water production more quickly than predicted.

CBNG water production in the Wyoming portion of the PRB reached a high in May of 2002 at 53,939,587 bbls and has decreased to a volume of 44,113,095 bbls as of April of 2004. During that same period the number of CBNG producing wells increased from 9,196 to 12,480. Through the period of May 2002 to April of 2004, the average rate of groundwater production from each CBNG well decreased from a rate of 5.5 gpm (188 bpd) to a rate of 3.4 gpm (116 bpd). The Wyoming FEIS (BLM, 2002) estimated that an additional 9,997 new CBNG wells would be drilled by the end of 2003. This number, combined with the 12,077 drilled or permitted CBNG wells at the time the FEIS was published, would yield a total of 22,074 wells predicted to have been in place by the end of 2003. In December 2003 there were a total of 12,465 producing wells within the PRB of which 12,145 were producing in Wyoming and 320 were producing in Montana. The fact that fewer wells are producing than projected likely contributes to the lower than predicted volumes of produced water.

Montana CBNG Produced Water

CBNG production from the Montana portion of the PRB is currently occurring only within the CX Ranch Field located in the southern portion of Big Horn County within the Montana PRB, just north of the Montana/Wyoming border. Production at CX Ranch began in April of 1999 with eight producing wells and a produced water quantity of 167,145 bbls for that month. As of April of 2004 there are 407 CBNG wells producing within the CX Ranch Field with a produced water quantity of 1,245,588 bbls/month. Computer modeling of CBNG development for the Montana portion of the PRB began with the year 2004 so comparisons to actual water production rates are not impossible at the present time.

Drilling below an On-Channel CBNG Impoundment in the Prairie Dog Creek Watershed, Wyoming

Coal Seam Aquifer Drawdown

The year 2003 annual monitoring report for the CX Ranch Field (the only CBNG producing field in Montana) contains information on groundwater drawdown that have occurred within the producing coal zones since production started in October, 1999 (Fidelity, 2004). At the end of 2003 there were a total of 327 CBNG wells producing from four Fort Union coal zones within the CX Ranch field: the Dietz 1 coal, the Dietz 2 coal, the Monarch coal, and the Carney coal. Cumulative water production from the CBNG field was approximately 14,950,000 bbls per year (between 8% and 24% of the volume predicted in BLM's model to support the Montana Oil and Gas EIS). Baseline groundwater levels were established for the CX Field in 1999 prior to the start of CBNG production.

The extent of actual drawdown is less than that predicted from the modeling and suggests that the predictive models used in the Wyoming and Montana EIS's were pessimistic. Less total CBNG water is being produced in the basin and specifically in the CX Ranch field. Impacts to groundwater aquifers have been less wide-spread than the model predicted. In addition, the coal thickness used in the MBMG model (10 feet to 30 feet) was pessimistic. While 205 wells were completed in coals 20 feet or less in thickness, 95 wells encountered coals thicker than 30 feet, and ten wells were completed in coals over 80 feet thick.

GROUNDWATER AQUIFERS IN THE POWDER RIVER BASIN

Groundwater quality within the various producing coal zones varies considerably, based on the specific chemistry of the differing coal zones. Three groups of coal seams need to be discussed separately – Wasatch coals, the Upper Fort Union coals (Wyodak through Carney), and the Lower Fort Union coals (Big George).

Wasatch (Lake De Smet and Felix Coal Zones)

Groundwater quality parameter concentrations for the Lake De Smet coal are consistently higher than the Felix coal for almost all parameters except for chloride which is higher in the Felix coal and SAR which is essentially equal with median values of 17.9 for the Felix coal and 18 for the Lake De Smet coal.

Lower Fort Union Coals

Water quality parameters for the Fort Union Formation are generally higher than for the Wasatch formation with the exception of calcium and magnesium. The lower median concentrations for calcium and magnesium within the Fort Union Formation, combined with a higher median concentration of sodium, combine to give a higher SAR value for the Fort Union.

Big George Coals

The Big George is a massive coal near the base of the Fort Union coal sequence; few coals exist below the Big George in the PRB. The Big George only is productive near the axis of the PRB and does not appear to extend into the Montana portion of the basin. The Big George appears to be stratigraphically separate from the shallower Fort Union coals and may contain slightly different water. There are, however, comparatively few wells that have been completed in the Big George and little water quality data has been collected.

Montana Coal Aquifers

Only one CBNG field exists in Montana but three main Upper Fort Union coal seams are productive. Water quality is consistent throughout this field with waters of medium quality that are high in SAR. The CX Ranch waters are similar to waters produced from several CBNG fields just south in Wyoming; these fields are very close to the axis of the PRB. This water is acceptable for livestock and wildlife and can be used for irrigation with careful management.

Alluvial Aquifers

The water quality of alluvial aquifers in the PRB is dependent upon the mineralogy of the alluvial sediment and the quality of the water in the surface stream in contact with the alluvium. Recharge to the alluvium is greatest when flows are highest in the river. During low-flow periods the river’s flow is dominated by base-flow groundwater discharges from the alluvium. Data collected by Ringen and Daddow from monitoring wells located in the alluvium near the Powder River; showed the water levels in the alluvium are influenced by flows in the river, with the degree of influence being proportional to the distance from the river. A well completed within 50 feet of the stream bank showed a larger and quicker response to changes in the river’s flow than a well located 450 feet from the stream bank.

CONCLUSIONS

Surface and groundwater data as well as data on CBNG production point to a number of conclusion concerning the impacts of CBNG development in the PRB on water resources.

1. **Drought Effects**: Surface water resources have been profoundly affected by the recent five-year drought. Since 1999, precipitation has decreased 27% in an extended drought.

a. The drought removes approximately 119 billion bbls of water each year from the basin. This figure is 200 times the 0.52 billion bbls of total CBNG water produced last year in the basin and over 600 times the 0.18 billion bbls of CBNG water discharged to the surface.

b. The drought has caused a reduction in main-stem flows from 86% in the Cheyenne River to 42% in the Tongue River.

c. Snow-melt during the drought is non-existent in the Cheyenne, Belle Fourche, Little Powder, and Powder Rivers. These rivers are now only fed by base-flow and scattered summer rain storms.

d. Base-flow is lower in quality than precipitation; as a result, drought affected streams now contain lower quality water.

2. **Surface Water**: The main-stems of the five watersheds with CBNG production in the PRB flow at the approximate combined drought rate of 2.8 billion bbls/year. CBNG wells produced approximately 0.52 billion bbls last year and discharged approximately 0.18 billion bbls to the surface. Water quality has not been seen to be affected by CBNG water discharges. The Powder River Watershed is typical with 4057 active CBNG wells, 1,141 permitted impoundments, and 273 permitted discharge points. Total surface discharge amounted last year to approximately 8.7% of the main-stem flow but average EC was not significantly different and SAR actually decreased from pre-CBNG values.

3. Groundwater: CBNG produced water reached the highest level of production to date in the basin during May 2002; it has been steadily declining since that time despite the fact that more active wells are being added all the time.

a. CBNG impacts to groundwater appear to have been exaggerated in an effort to be as conservative as possible. In fact, after three years of production, Dietz-Anderson coal seams show a draw-down radius less than 2,100 feet from the edge of active production.

b. Other non-coal aquifers are well isolated from productive coal seams; more than 50% of the basins alluvium wells are less than 30 feet deep, much shallower than CBNG production that is only rarely less than 400 feet deep.

GENERAL SITING CRITERIA FOR CBNG IMPOUNDMENTS

There are a number of variables that are critical in the final determination as to how a surface impoundment will perform over the term of its use as a management tool for handling CBNG produced water and what if any impact that use will have on the surrounding environment. These siting variables are both dynamic, and often interrelated. And to certain extent they can be evaluated in the initial planning stage by a careful review of available data directly and indirectly related to those siting variables.

In addition to the kind of impoundment to be constructed, on-channel verses off-channel, these variables include information related to geomorphology, site topography, surface and groundwater conditions, surface geology, soil type, hydrogeology, and vegetation. This section focuses on those variables from a local and regional perspective within the PRB as they relate to the planning phase for siting a CBNG impoundment.

IMPOUNDMENT TYPES - ON CHANNEL IMPOUNDMENTS

On-channel impoundments are generally defined as any impoundment established in an existing surface water drainage path by the construction of a dam, or embankment, across that drainage pathway. Data from the office of the Wyoming State Engineer indicates that there are nearly 2,000 surface impoundments in the Wyoming portion of the Powder River Basin. Approximately 31% (620) of those impoundments are classified as on-channel impoundments by the WSEO. That number does not however include on-channel impoundments in upland areas that are not on or immediately adjacent to alluvial deposits but would still be considered on-channel impoundments. Figure 3-1 depicts where the existing impoundments classified as on-channel exist in the Powder River Basin of Wyoming. Approximately 52.7% of the existing on-channel impoundments are located in the Powder River watershed, with 19.1% in the Belle Fourche watershed and 13.3% in the Cheyenne watershed. Just over 100 on-channel impoundments are located are located in the Little Powder and Tongue River watersheds.

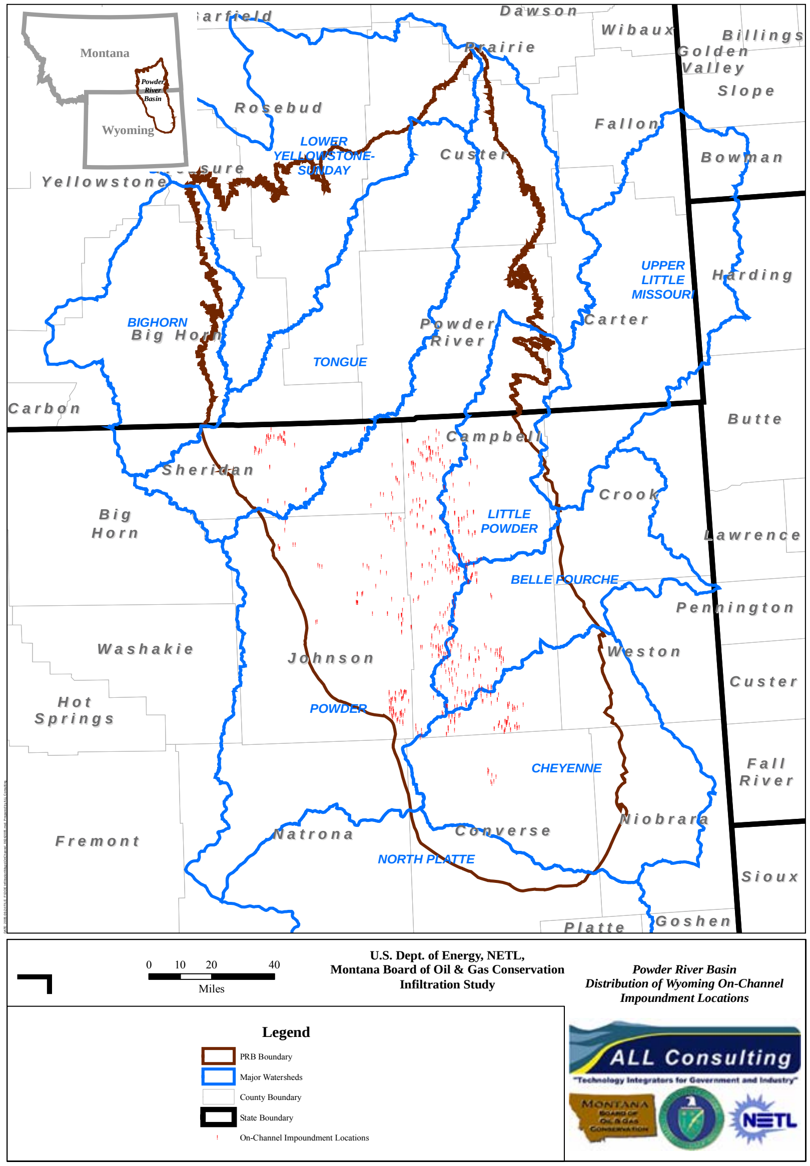
On-channel CBNG water management impoundments can be developed in two distinct ways:

1. through the construction of a new on-channel impoundment on an identified water drainage way; or
2. by conversion of an existing on-channel impoundment for use as a produced water impoundment.

Both of these on-channel alternatives have positive and negative aspects which are related to both economic and technical criteria.

For newly constructed on-channel impoundments those include:

Figure 3-1: Existing On-Channel Impoundments



Positive Aspects:

- Planning and design allows the impoundment to be centrally located so that transportation and infrastructure costs are minimized.
- Overall cost to manage produced water is lower than for alternative management options.
- Infiltration rates are generally higher in alluvium, thus enabling a greater potential for water management. Alluvium has a tendency to have less geochemical impact on infiltrating water than shaley bedrock.

Negative Aspects:

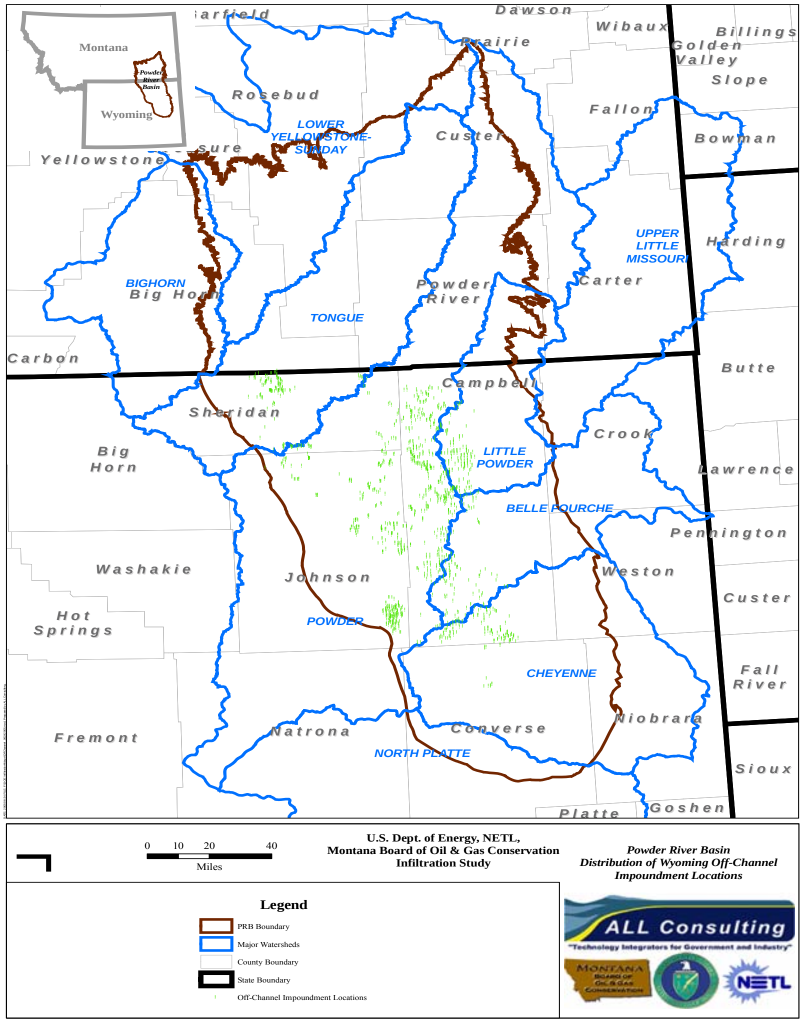
- Planning, design, and construction of the system can be costly.
- Impoundment performance may not match the design life of the structure due to the tendency of the substrate to seal itself off with use.
- Adverse groundwater impacts may be encountered due to presence of minerals, metals, and ions in the soil mobilizing into the infiltrating water.
- Potential for "direct" discharge to surface waters.
- Permitting process may be more extensive than for converted impoundments or off-channel impoundments.
- Water Rights Issues associated with the potential to reduce downstream water quantity and quality.

For existing on-channel impoundment conversions those include:

Positive Aspects:

- Construction costs can be reduced compared to a newly-constructed impoundment.
- Previous use of the impoundment may have flushed the soil, alluvium, and bedrock beneath the impoundment of soluble minerals, metals, and ions thereby reducing the possibility of adverse impacts to groundwater.
- Existing beneficial uses such as livestock watering and wildlife habitat can be continued and perhaps increased.
- Infiltration rates may already be known from historical use as a stock pond.
- Groundwater quality under an existing impoundment may already be lower than other on-channel areas due to previous infiltration.

Figure 3-2: Existing Off-Channel Impoundments



Negative Aspects:

- Impoundment performance may not meet the design life because reduced permeability may have already occurred through previous use.
- Cost of associated infrastructure (pipe, roads, etc) may be higher.
- Potential for "direct" discharge to surface waters may exist if the alluvium layer is thin and an impermeable layer is encountered at a shallow depth.
- Impoundment may have already developed a leak prior to conversion
- Impoundment locations within the drainage channel are more vulnerable to damage from storm water runoff events.

IMPOUNDMENT TYPES - OFF-CHANNEL IMPOUNDMENTS

Off-channel impoundments are defined as any impoundment constructed by excavation in a nearly level area outside of an existing stream channel or intermittent watercourse. Of the nearly 2,000 surface impoundments in the Wyoming portion of the Powder River Basin identified by the WSEO approximately 69% (1,364) are classified as off-channel impoundments. Figure 3-2 depicts where the existing impoundments classified as off-channel exist in the PRB of Wyoming. Approximately 64.4% of the existing off-channel impoundments are located in the Powder River watershed, with 12.7% in the Little Powder River watershed and 10.2% in the Cheyenne watershed. The Tongue and Belle Fourche watersheds contain the remaining 135 existing off-channel impoundments which represents approximately 17.2% of the total off-channel impoundments in the Wyoming portion of the PRB.

As with on-channel impoundments, off-channel CBNG water management impoundments can also be developed in two ways:

1. through the construction of a new off-channel impoundment; or
2. by conversion of an existing off-channel impoundment for use as a produced water impoundment.

Both of these alternatives have positive and negative aspects, which as with on-channel impoundments, are related to both economic and technical criteria.

For newly constructed off-channel impoundments those include:

Positive Aspects:

- Planning and design allows for the impoundment to be ideally located so that transportation and infrastructure costs can be minimized.
- Overall cost to manage produced water may be lower than for alternative management options.
- Beneficial uses such as livestock watering and wildlife habitat can be established, opening up new areas for grazing and recreational use and helping the surface owner.
- Planning and design allows for the impoundment to be located in geologically attractive areas where infiltration rates are higher.
- There is a reduced potential for infiltrated water to resurface via a hydrologic connection to nearby surface water.

Negative Aspects:

- Planning, design, and construction of the system can be expensive.
- Performance of the impoundment may not meet the design life because of the nature of the soil which may result in reduction or loss of infiltration over time.

- Adverse groundwater impacts may be encountered due to presence of minerals, metals, and ions in the soil or bedrock mobilizing into the infiltrating water which eventually contacts existing groundwater.
- Infiltrating groundwater may encounter an impermeable layer which causes the water to migrate horizontally and discharge to the surface from a hillside.

For existing off-channel impoundment conversions those include:

Positive Aspects:

- Construction costs are minimal as compared to a newly-constructed impoundment.
- Adverse groundwater impacts may not be a problem as an existing impoundment may have already "flushed" the underlying soil of soluble minerals, metals, and ions.
- Overall cost to manage produced water may be lower than for alternative management options.
- Beneficial uses such as livestock watering and wildlife habitat can be continued and perhaps increased.

Negative Aspects:

- Performance of the impoundment may not meet the design life because of the nature of the soil which may result in reduction or loss of infiltration over time.
- Cost of infrastructure (pipe, roads, etc) may be higher due to the location of the existing impoundment and the proximity to CBNG wells.
- Size of existing impoundment may not be sufficient to meet water management needs.

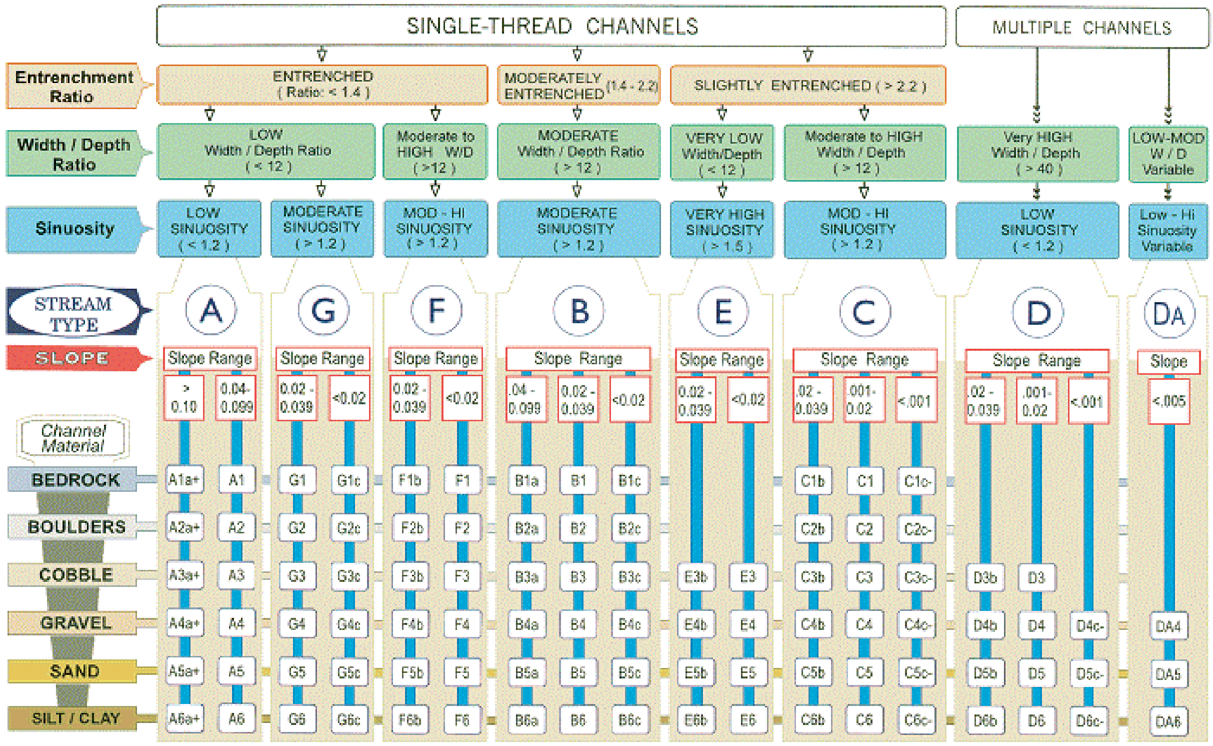
GEOMORPHOLOGY / STREAM AND SURFACE WATER MORPHOLOGY

On-channel impoundments make use of natural channels that may be occupied by surface water systems. These surface water systems are dynamic in nature and capable of adapting to changes in climate or other developments that alter the watershed. These adaptations occur as a result of a stream's natural tendency to reach a dynamic equilibrium between flow, the physical geomorphic properties of the system, and load. These factors include: discharge, width, depth, velocity, slope, channel roughness, sediment load, and sediment size/volume (US Fish and Wildlife, 2000).

Geomorphology can impact the decision making process of where to site an on-channel impoundment by assessing the potential impact the impoundment could have on the stability of the existing or nearby surface water systems. An initial step in making that assessment is a classification of the stream or river system on which any on-channel impoundment is to be placed.

A stream classification system for natural waterways developed by David Rosgen has been adopted by many workers assessing surface waters systems (Rosgen, 1994). The classification methodology shown in Fig 3-3 includes evaluations related to a number of physical properties of streams including: channel type, entrenchment, width to depth ratio, sinuosity, slope, and type of channel material. A description as to the use of this system in determining a class type for a particular stream is contained in *Siting, Design, Construction, and Reclamation Guidebook for Coalbed Natural Gas Impoundments* (All Consulting, 2006) or the reader is referred to a U.S. EPA website (www.epa.gov/watertrain/**stream**_class/) which also provides details as to the use of this classification system.

Figure 3-3: Chart of the Rosgen Classification of Streams



KEY to the ROSGEN CLASSIFICATION of NATURAL RIVERS. As a function of the "*continuum of physical variables*" within stream reaches, values of ***Entrenchment*** and ***Sinuosity*** ratios can vary by +/- 0.2 units; while values for ***Width / Depth*** ratios can vary by +/- 2.0 units.

(Rosgen, 1994)

Once the surface water systems on which on-channel impoundment are being considered have been classified according to the Rosgen system certain interpretations can be made relating to that stream's suitability for placement of on-channel impoundments.

Table 3-1 can be used to determine the level of impact an impoundment might have on the existing system, which in turn can be used as a guide for siting criteria in the planning process.

Table 3-1: Management Interpretations for Natural Stream Types

Stream Type	Sensitivity to Disturbance[a]	Recovery Potential[b]	Sediment Supply[c]	Streambank Erosion Potential	Vegetation Controlling Influence[d]
A1	very low	excellent	very low	very low	negligible
A2	very low	excellent	very low	very low	negligible
A3	very high	very poor	very high	very high	negligible
A4	extreme	very poor	very high	very high	negligible
A5	extreme	very poor	very high	very high	negligible
A6	high	poor	high	high	negligible
B1	very low	excellent	very low	very low	negligible
B2	very low	excellent	very low	very low	negligible
B3	low	excellent	low	low	moderate
B4	moderate	excellent	moderate	low	moderate
B5	moderate	excellent	moderate	moderate	moderate
B6	moderate	excellent	moderate	low	moderate
C1	low	very good	very low	low	moderate
C2	low	very good	low	low	moderate
C3	moderate	good	moderate	moderate	very high
C4	very high	good	high	very high	very high
C5	very high	fair	very high	very high	very high
C6	very high	good	high	high	very high
D3	very high	poor	very high	very high	moderate
D4	very high	poor	very high	very high	moderate
D5	very high	poor	very high	very high	moderate
D6	high	poor	high	high	moderate
DA4	moderate	good	very low	low	very high
DA5	moderate	good	low	low	very high
DA6	moderate	good	very low	very low	very high
E3	high	good	low	moderate	very high
E4	very high	good	moderate	high	very high
E5	very high	good	moderate	high	very high
E6	very high	good	low	moderate	very high
F1	low	fair	low	moderate	low
F2	low	fair	moderate	moderate	low
F3	moderate	poor	very high	very high	moderate
F4	extreme	poor	very high	very high	moderate
F5	very high	poor	very high	very high	moderate
F6	very high	fair	high	very high	moderate
G1	low	good	low	low	low
G2	moderate	fair	moderate	moderate	low
G3	very high	poor	very high	very high	high
G4	extreme	very poor	very high	very high	high
G5	extreme	very poor	very high	very high	high
G6	very high	poor	high	high	high

a Includes increases in streamflow magnitude and timing and/or sediment increases.
b Assumes natural recovery once cause of instability is corrected.
c Includes suspended and bedload from channel derived sources and/or from stream adjacent slopes.
d Vegetation that influences width/depth ratio-stability.

As an example streams classified as “G6” streams should be avoided due to their very high sensitivity to disturbance, poor recovery potential, high sediment supply, high erosion potential, and the high dependence on vegetation to control stability. Stream classifications that may be present in rivers and tributaries of the PRB are represented by a broad range of stream types that are included in Table 3-1. Consideration should be given to all five of the sensitivity factors shown on this table when locating and planning an on-channel impoundment.

TOPOGRAPHY

Site topography is perhaps the most influential siting criteria considered when developing impoundments. Topography plays such an important role because it has the potential to dramatically reduce construction costs by starting with a site that has a natural affinity for impoundment siting.

Significant factors related to site topography that should be considered prior to choosing an on-channel impoundment site include: existing side slope ratios and channel width at the base of the proposed impoundment. These factors can affect the drainage area with associated influx of sediment, the effective capacity of the impoundment, as well as construction costs for associated dam and embankment placement.

Topographic consideration when siting an off-channel impoundment in uplands are generally related to siting impoundments in such a manner as to reduce the likelihood of an unintended discharge to the surface through lateral infiltration. Failure to recognize such conditions prior to siting impoundments on elevated locations may result in discharges at lower elevation outcropping locations and depending the permit and seepage volume could lead to regulatory violations

GEOLOGY, SOILS, AND HYDROGEOLOGY

Through an understanding of the surficial and near-surface geology of an area, one can determine the extent to which an area is suitable for the use of infiltration as a water management practice, and the changes that may need to be incorporated into the impoundment design for any given site. The geologic conditions present across the PRB can vary enough so that even within a single producing field variations can result in different design criteria for each impoundment.

Understanding bedrock and outcrop geology will aid in determining if the water that infiltrates through the strata of the PRB will be contained within these formations as groundwater or discharged to surface water or springs. Additionally, an understanding of the mineralogy of the bedrock underlying the soils and strata that occur within the an area can assist in predicting potential geochemical changes which may occur as infiltrating water comes into contact with these materials.

Figure 3-4: Geologic Outcrop Map of the PRB

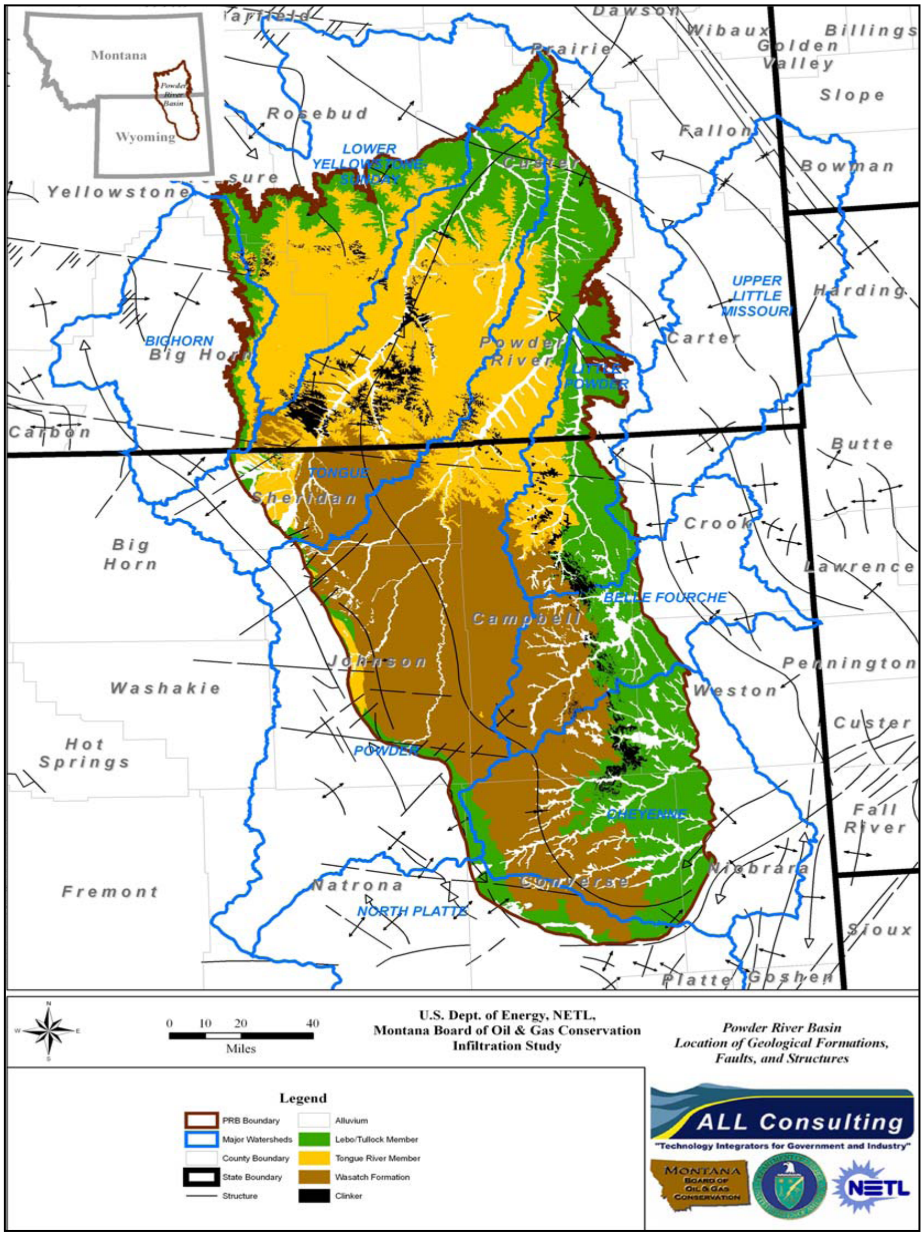


Figure 3-4 is a surface geologic map for the Powder River Basin and illustrates the broad shape of the basin outline and the outcrop pattern for geologic strata exposed at the surface. Figure 3-4 also shows the course of the major rivers that cross the PRB, which are areas where alluvium deposits dominate. The alluvium present along these rivers is reworked sediments eroded from the other formations and redeposited by rivers. Also illustrated on the outcrop map is the presence of coal clinker associated with outcrops of the Wasatch and Fort Union formations within the basin. These coal clinker outcrops represent the recharge zones for the coal aquifers in the central part of the PRB.

The stratigraphic column presented as Figure 3-5 shows the major geologic formations including destratigraphy of the PRB includes sands, coals, fluvial deposits, and other fine-grained sediments, including details as to the position of the coal seams of the Wasatch and Fort Union Formations. These coal units are of particular interest in the PRB because they are the source of CBNG production both for natural gas and produced water, as well as being widespread aquifers which are utilized for drinking and agricultural use.

Figure 3-5: Stratigraphic Column Tertiary Section for the Powder River Basin

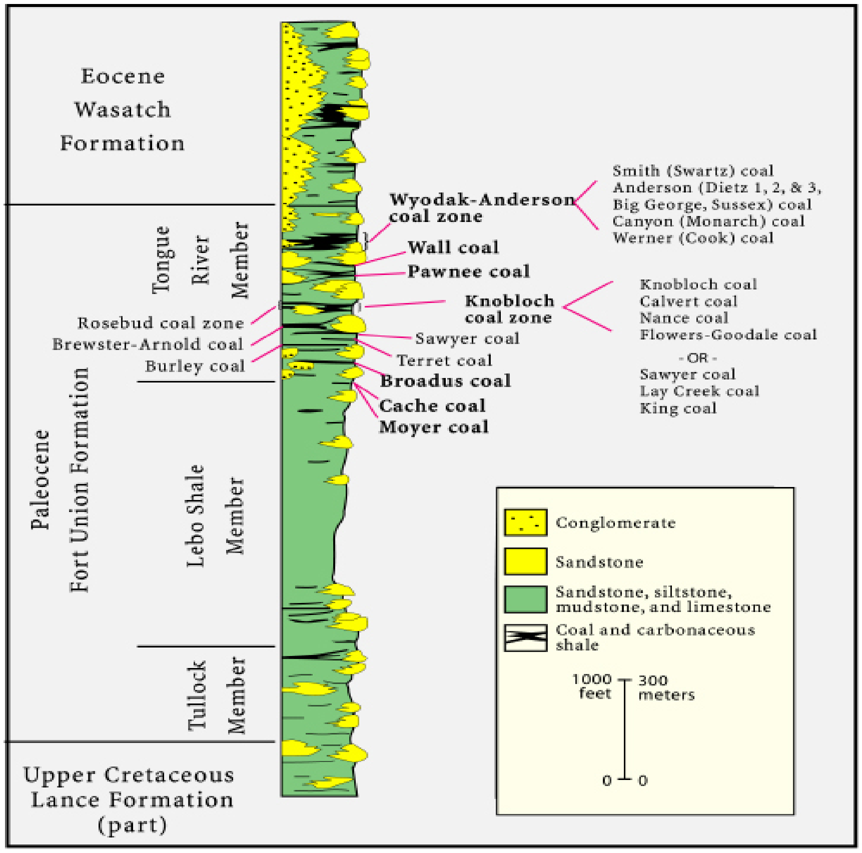


Table 3-2 provides hydrogeologic data for the various shallow geologic formations which occur in the PRB. The table presents characteristic ranges of values for aquifer thickness, water yields, water quality, and depth for the different formations. Additionally, information related to the lithologic composition and infiltration classification is provided. Infiltration classification includes the ability to infiltrate water and the possible impact that water may have on CBNG development and on regulatory concerns such as discharge to surface waters or seepage of the water at nearby outcrops.

Table 3-2: Hydrogeologic Properties of Formation Present at the Surface in the PRB

Outcrop Unit (Age)	Thickness (feet)	Lithologies	Water Availability	Water Quality	TDS (mg/L)	K Value (ft/s)	Infiltration Classification	Depth (feet)
Alluvium (Quaternary/Recent)	10 to 40, as high as 90	Unconsolidated silt, sand, and gravels	Yields to 1,000+ gpm	Good to poor	400 to 9,000	1×10^{-7} to 4.1×10^{-3}	High infiltration rates, may impact area streams, may breakout to surface	Shallow
Ft. Union Coals (Paleocene)	10 to 50	Coal with clay	Yields to 30 gpm	Good to poor	400 to 2,800	4.6×10^{-7} to 8.6×10^{-4}	High infiltration rates, may impact CBNG prod., may breakout to surface	Up to 2500
Ft. Union Clinker (Recent)	5 to 50	Baked coal and clay	Very high	Good		2×10^{-5} to 6×10^{-6}	Very high, may breakout to surface	Shallow
Ft. Union Sands (Paleocene)	5 to 50	Clayey sand	Yields less than 10 gpm, average much less	Poor	2,100 to 3,000	4.1×10^{-6} to 4.1×10^{-4}	Rates medium to low. Some sands appear to be persistent, most do not	Up to 4,000
Ft. Union Claystones (Paleocene)	10 to 50	Claystone, shale	Aquitards	None	N/A	8.1×10^{-8}	Poor	Up to 4,000
Wasatch Sands	5 to 50	Lenticular sandstones, interbedded with fines	Yield 10 to 500 gpm, average 10 to 50 gpm	Good to poor	600 to 4,000	2.3×10^{-7} to 2.3×10^{-4}	Medium to low. Sands are discontinuous, lenticular, with fines present.	Up to 800

As noted above, important outcropping units in the PRB include Quaternary Alluvium and Eocene and Paleocene aged clastic and coal deposits of the Wasatch and Fort Union Formations (see Figure 3-4). The structural configuration, lithology, mineralogy, and hydrology of these units can have a significant influence on both placement and design consideration of CBNG impoundments.

Alluvium

Alluvium consists of unconsolidated sand, silt, and gravel that make up the floodplains and stream terraces of creek valleys in the PRB (BLM, 1999). As shown on Figure 3-4 alluvium is present in the PRB along the major rivers. Thickness of the alluvium varies across the basin with total thickness generally less than 90 ft. Near the Powder River the thickness ranges from 4 ft. to 45 ft. thick but is commonly in the 10 to 30 ft. range (Ringen and Daddow, 1989). Finer-grained alluvial material will likely have a lower hydraulic conductivity than the coarser material. Mineralogy is also likely to be different with more soluble material present in alluvium derived from Tertiary sediments.

Research by Ringen and Daddow (1989) has demonstrated that the water in the alluvium around the Powder River is primarily derived from seepage when streamflow is high; the groundwater then discharges back into the river during periods of low flow. Because of this interaction between the groundwater in the alluvium and surface water in the rivers, any water that is allowed to infiltrate into the alluvium has the potential to be discharged directly to surface streams during periods of low flow. This interaction makes the alluvial environment vulnerable to changes from on-channel impoundments.

The geometry of alluvial deposits and the relationship of those deposits to local and regional hydrology can be quite complex and can affect the volume of water that can be infiltrated. An impoundment site with lateral continuity of alluvium and thick deposits of porous and permeable, unsaturated alluvium has the potential to receive and distribute large volumes of infiltrating water. By defining the aerial extent of the alluvium, internal flow-units, and estimating the porosity and permeability of the alluvial compartment, calculations of the receiving capacity can be performed to help define the capacity for any impoundment. Table 3-3 includes a summary of both the pros and cons of constructing an impoundment in an area with alluvium as a base material.

Coal and Coal Clinker

As shown in Figure 3-5, coal deposits are prevalent in the upper part of the Fort Union Formation and in the Wasatch Formation. At depth these coals are productive of CBNG. At or near surface these coal units of the Fort Union are represented by coal clinker deposits which are formed by the natural burning of coal beds and the resultant baking or fusing of clayey strata overlying the burning coal. Coal clinker deposits are present throughout much of the PRB (Tudor, 1975). As a result of the baking, the clinker deposits are resistant to erosion by water and wind, so many of the hilltops within the PRB are capped by clinker (Heffern and Coates, 1997). Baking also greatly increases porosity as well as horizontal and vertical permeability of the clinker, allowing clinker beds to accept large volumes of infiltrate. Figure 3-4 illustrates the distribution of the coal clinker along the eastern side of the PRB in Wyoming and the south central region of the PRB in Montana.

Design considerations for constructing impoundments on clinker deposits are related to identifying and understanding the location, structural attitude, and stratigraphic distribution of the clinker.

Research on coal seam aquifers report that the coal clinker deposits are highly permeable and act as recharge zones for coal seams and other underlying aquifers of the Wasatch and Fort Union Formation (Moreland, 1987; Heffern and Coates, 1999; and Bartos and Ogle, 2002). In siting impoundments or such deposits it is important to assess local geologic conditions respective to these deposits so that infiltration does not impact down-dip coal seams that are productive of CBNG or that infiltration does not result in surface discharge at outcrops or springs emanating from such deposits. Table 3-3 includes a summary of both the pros and cons of constructing an impoundment in an area with coal clinker as a base material.

Wasatch and Fort Union Formations

The Wasatch Formation and underlying Tongue River Member of the Fort Union Formation are geologically similar and consist of irregular and discontinuous sandstones with interbedded finer-grained siltstones, claystones, mudstones and some coals (Bartos and Ogle, 2002). As shown in Figure 3-4 the outcrop of the Wasatch Formation is primarily limited to the central and western portions of the PRB in Wyoming. The Fort Union Formation's Lebo/Tullock Members outcrop along the eastern side of the basin in Wyoming and continue northward into Montana along the northern boundary. The Tongue River Member outcrops along the central portion of the basin in Montana. The Wasatch Formation is present at the surface throughout the central part of the Wyoming portion of the PRB. Similarities in the lithological composition and depositional history make differentiation of the Wasatch Formation from the Tongue River Member of the Fort Union Formation difficult (Ellis, et. al. 1999). Localized differences such as changes in sand and silt content; clay mineralogy; gypsum and other mineral content; and bedding characteristics can all be important when designing impoundments over these formations. Finely divided mineral content in these Tertiary beds can degrade infiltrate as it moves through these units.

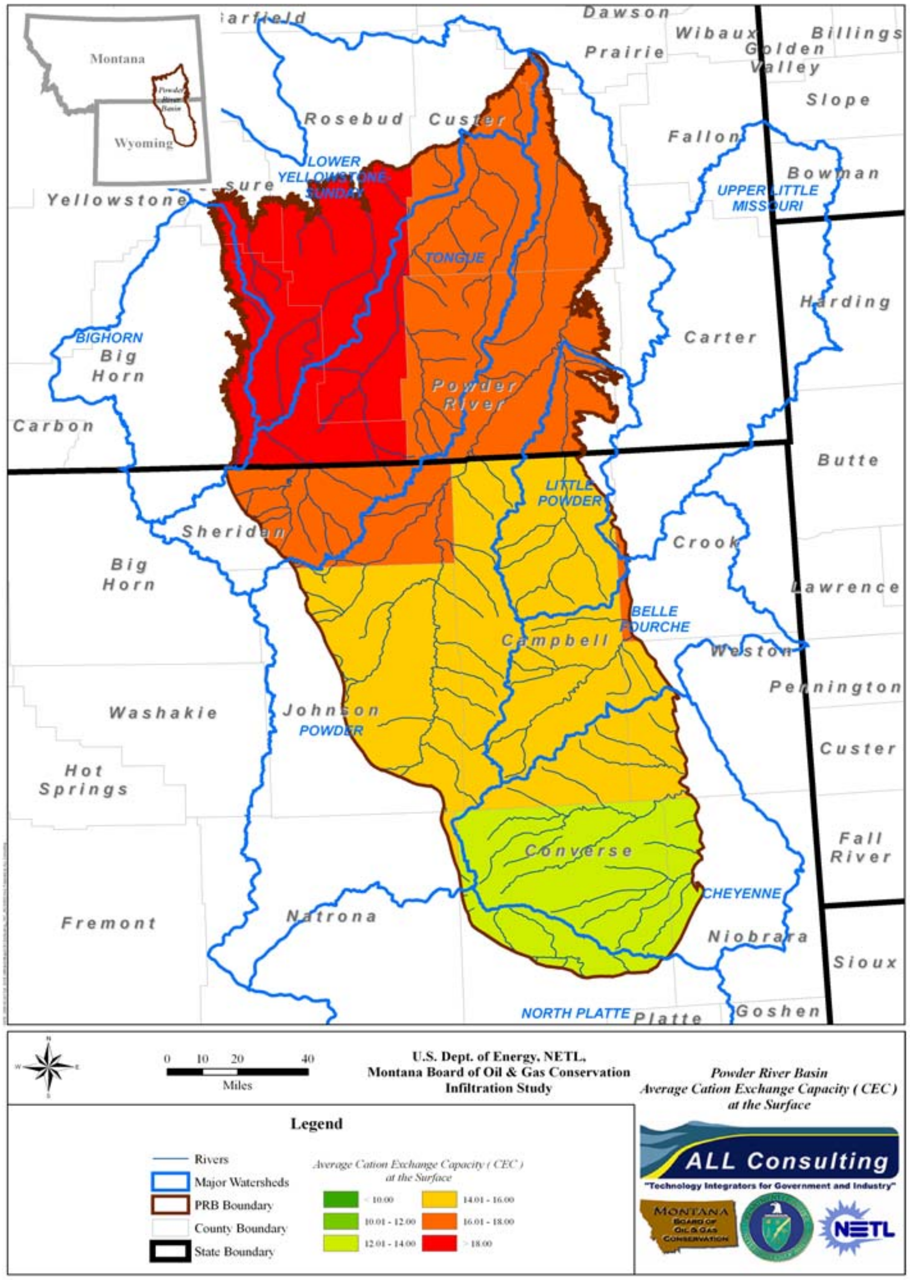
Table 3-3: Pros and Cons of Constructing an Impoundment Over Various Geological Formations

Outcrop Unit (Age)	Pros	Cons
Alluvium (Quaternary/ Recent)	• High infiltration rates can lead to managing greater volumes of water in less time • Increased discharge rates of alluvial water to the river may be experienced, providing more water to surface users	• Infiltration rates may be impacted during high surface flows due to less available pore space • Mineral content in vadose zone may cause infiltrating water quality to degrade • Faults and/or fissures in the claystones underlying the alluvium may provide a pathway for water to infiltrate to deeper aquifers • Surface breakouts are possible, leading to regulatory violations
Ft. Union Coals (Paleocene)	• The Fort Union unit makes up a large percentage of the outcrops in the PRB • High infiltration rates can lead to managing greater volumes of water in less time	• Recharge of coal seam may impact CBNG production • Nearby coal outcrops may serve as a source for water to discharge to the surface, leading to regulatory violations

Outcrop Unit (Age)	Pros	Cons
Ft. Union Clinker (Recent)	• High infiltration rates can lead to managing greater volumes of water in less time • Water quality in the clinker is good	• Recharge of coal seam may impact CBNG production • Nearby clinker outcrops may serve as a source for water to discharge to the surface, leading to regulatory violations
Ft. Union Sands (Paleocene)	• The Fort Union unit makes up a large percentage of the outcrops in the PRB • May provide higher infiltration rates than finer grained claystones, mudstones, and siltstones	• Mineral content in vadose zone may cause infiltrating water quality to degrade • Identifying ideal soil chemistry can be costly • Sandstones may not be present at the required design depth • Faults and/or fissures in the claystones underlying the sandstones may provide a pathway for water to infiltrate to deeper aquifers
Ft. Union Claystones (Paleocene)	• Not conducive for infiltration through impoundments	• Low infiltration rates unless faults/fissures exist • If present, faults and/or fissures may provide a pathway for water to infiltrate to deeper aquifers • Mineral content in vadose zone may be much higher due to the nature of the claystone to hold water use infiltrating water quality to degrade
Wasatch Sands	• The Wasatch unit makes up a large percentage of the outcrops in the PRB • Sandstones present may provide medium to low infiltration rates • Sandstone may also lessen impacts on infiltrating water quality (as compared to claystones, mudstones, and siltstones)	• Mineral content in vadose zone may cause infiltrating water quality to degrade • Identifying ideal soil chemistry can be costly • Sandstones may not be present at the required design depth • Faults and/or fissures in the claystones underlying the sandstones may provide a pathway for water to infiltrate to deeper aquifers

Design considerations for the Wasatch and Fort Union Formation consist of identifying sites where infiltration can be maintained with minimal change to the chemical character of the infiltrating water. Table 3-3 includes a summary of both the pros and cons of constructing an impoundment in an area with strata of the Fort Union or Wasatch Formations as a base material.

Figure 3-6: Average Cation Exchange Capacity for Surface Soils by County



Soils

Surface and subsurface soils can present another variable which can effect changes to infiltrating water chemistry and therefore play a role in the siting of impoundments, particularly on-channel impoundments. Understanding the types of soils present near on-channel impoundments can lead to information relative to the clay content, cation-exchange capacity, and the percentage of certain soluble mineral assemblages in the soils each of which can cause changes to the infiltrating water chemistry.

Table 3-4: Geochemical Data for the Shallow Surface Soils of the PRB by County

Wyoming	**Cation Exchange Capacity**				**Percent Calcium Carbonate**				**Percent Gypsum**			
Counties	*Avg.*	*Min*	*Max*	*Std Dev*	*Avg.*	*Min*	*Max*	*Std Dev*	*Avg.*	*Min*	*Max*	*Std Dev*
Crook	16.5	0	42.5	7.91	1.15	0	22.5	2.28	0.20	0	37.5	2.31
Niobrara	13.4	4	35	6.15	1.03	0	12.5	1.89	0.01	0	2.5	0.17
Weston	15.2	3	37.5	7.01	1.88	0	12.5	2.77	0.05	0	2.5	0.28
Natrona	14.3	0	32.5	6.00	3.02	0	35	4.15	0.25	0	10	1.22
Sheridan	16.8	4.5	45	5.78	1.96	0	10	3.20	0.01	0	2.5	0.12
Campbell	15.1	3	49	6.42	0.76	0	5	1.07	0.02	0	2.5	0.21
Converse	12.6	3.5	32.5	5.65	1.85	0	20	2.80	0.01	0	2.5	0.15
Johnson	14.6	1.5	49	7.16	1.55	0	20	2.41	0.12	0	30	1.22
Montana	**Cation Exchange Capacity**				**Percent Calcium Carbonate**				**Percent Gypsum**			
Counties	*Avg.*	*Min*	*Max*	*Std Dev*	*Avg.*	*Min*	*Max*	*Std Dev*	*Avg.*	*Min*	*Max*	*Std Dev*
Carter	18.9	7.5	35	7.04	3.11	0	7.5	2.75	--	--	--	--
Custer	17.7	7.5	35	6.02	4.60	0	7.5	2.80	0.5	0	2.5	1.12
Prairie	16.5	3	35	5.96	2.38	0	7.5	3.25	0	0	0	--
Treasure	19.9	3	40	7.25	2.74	0	7.5	1.70	--	--	--	--
Bighorn	20.4	7.5	37.5	6.38	3.54	0	10	2.19	--	--	--	--
Powder River	18.0	7.5	32.5	5.63	4.51	0	7.5	2.72	--	--	--	--
Rosebud	19.2	7.5	37.5	6.48	1.89	0	10	2.67	0	0	0	0

Source data: SSURGO county data.

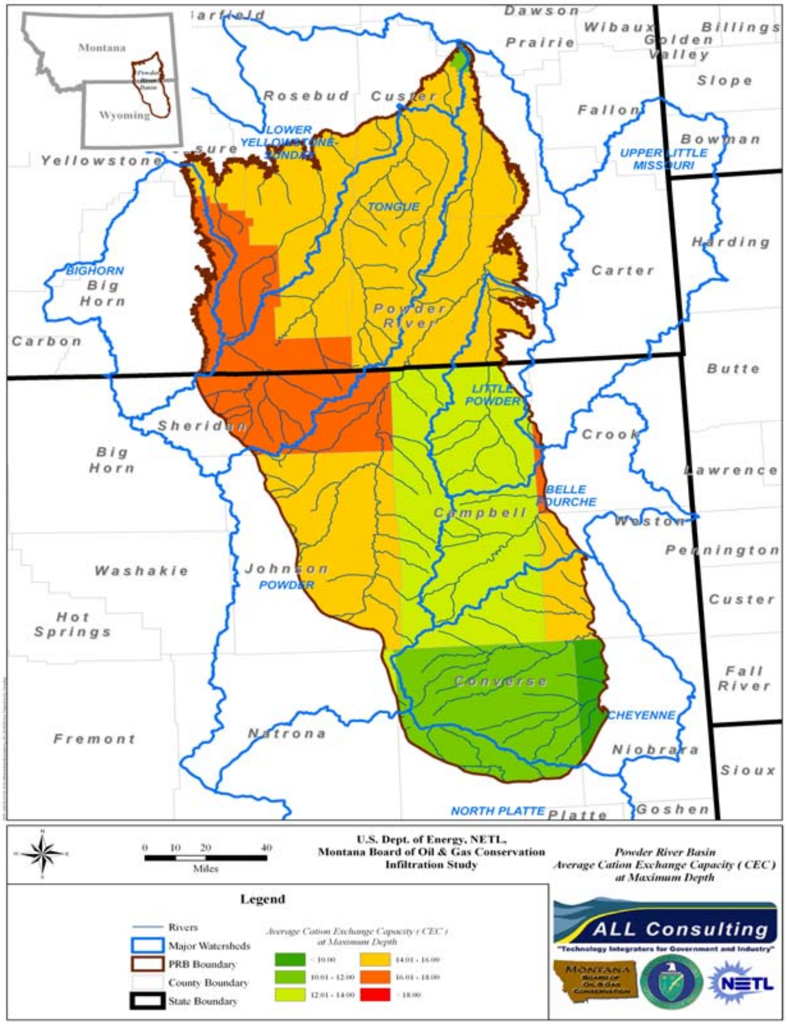
Table 3-5: Geochemical Data for the Maximum Depth Surface Soils of the PRB by County

Wyoming	**Cation Exchange Capacity**				**Percent Calcium Carbonate**				**Percent Gypsum**			
Counties	*Avg.*	*Min*	*Max*	*Std Dev*	*Avg.*	*Min*	*Max*	*Std Dev*	*Avg.*	*Min*	*Max*	*Std Dev*
Crook	16.0	0	41	8.18	6.06	0	27.5	5.03	0.34	0	12.5	1.17
Niobrara	9.93	2	25	6.06	5.96	0	20	4.52	0.05	0	3	0.36
Weston	15.3	0	32.5	7.46	6.81	0	20	3.68	0.13	0	3	0.49
Natrona	13.8	0	30	6.96	9.63	0	55	7.38	0.88	0	15	2.19
Sheridan	16.8	0	35	7.58	8.83	0	45	5.90	0.15	0	3	0.42
Campbell	14.0	0	42.5	7.97	7.03	0	10.5	3.64	0.24	0	3	0.43
Converse	12.0	0	34	7.78	6.85	0	35	4.79	0.21	0	7.5	0.84
Johnson	15.0	0	45.5	8.29	8.22	0	27.5	4.70	0.53	0	10	1.39
Montana	**Cation Exchange Capacity**				**Percent Calcium Carbonate**				**Percent Gypsum**			
Counties	*Avg.*	*Min*	*Max*	*Std Dev*	*Avg.*	*Min*	*Max*	*Std Dev*	*Avg.*	*Min*	*Max*	*Std Dev*
Carter	16.8	0.5	35	8.18	8.35	0	22.5	4.00	2.36	0.5	10	1.64
Custer	14.1	0	35	7.32	8.68	3	22.5	3.61	2.00	0	4	1.18
Prairie	11.5	0	27.5	7.19	5.80	0	12.5	4.49	2.27	0	10.5	1.86
Treasure	14.6	0.5	37.5	7.90	7.41	2.5	20	3.44	3.00	3	3	--
Bighorn	16.5	0	35	7.91	12.9	0	50	12.8	1.00	1	1	--
Powder River	15.1	1	27.5	6.19	9.16	2.5	20	4.37	--	--	--	--
Rosebud	14.1	0	40	6.90	5.37	0	30	5.52	2.92	0	15	2.15

Source data: SSURGO county data.

Tables 3-4 and 3-5 provide statistical summaries of the cation exchange capacity, percent calcium carbonate, and percent gypsum for surface soils and soils of maximum depth in the PRB, identified by county. The CEC data presented in these Tables illustrate the variation that can be seen in soils in the PRB; generally the shallow surface soils have higher average CECs than the maximum depth soils. The data also shows a difference in the average CEC of the shallow surface soils between the two states with the Montana soils having a higher average CEC than the Wyoming soils. Figures 3-6 and 3-7 shows the average CEC values for the shallow soils and maximum depth soil samples, respectively, within the counties of the PRB. The maps illustrate the higher average CEC in the shallow soils in the northern part of the basin with values decreasing toward the southeast of the basin.

Figure 3-7: Average Cation Exchange Capacity for Max Depth Soils, by County



Tables 3-4 and 3-5 also present statistical data for two soluble minerals commonly present in soils which can affect the quality of infiltrating water, CaCO3 (calcite) and gypsum. The tables show that these two soluble minerals are present in greater quantities at depth in the soil column. Within the PRB, these two soluble minerals are generally present in greater quantities in the Montana counties than in the Wyoming counties. And while data is somewhat limited there appears to be more gypsum present on average in the Montana soils at depth than in Wyoming soils.

Vegetation

The natural vegetation of most of the PRB is a mixture of grasses and sagebrush. Plains cottonwood trees commonly grow along stream bottoms in the plains, whereas breaks and upland areas may support thin stands of ponderosa pine and juniper. The vegetation of the western edge of the PRB reflects greater precipitation on the mountains than on the plains (USGS, 1986).

In addition to using vegetative types as a possible indication of higher soil permeability the type of vegetation can also be used to indicate the texture and geochemistry of the soil. Furthermore, vegetation can be used both during and after construction to protect slopes, uptake water from the soil, and establish a suitable and durable groundcover at the site.

Table 3-6 which was compiled from the USDA PLANTS database shows native species tolerance to salt and $CaCO_3$, as well as the potential for uptake of water and adaptability to various soil textures. The tolerance to $CaCO_3$ refers to the plant's relative tolerance of calcium carbonate in the soil, while the tolerance to salt refers to the plant's relative tolerance to saline soil conditions. The moisture use refers to the plant's relative moisture requirements for growth (USDA, 2004). During the investigation of the feasibility of a site, this table can be used to predict how well the native vegetation will sustain itself once the impoundment is in place, and identify areas where additional focus may be required to ensure proper vegetation of the site (once construction is complete).

Table 3-6: Native Vegetation Tolerance Levels for Salt and $CaCO_3$

Plant (common name)	Tolerance to Salt	Tolerance to $CaCO_3$	Moisture Use	Adapted to Soil Texture:		
				Coarse	Medium	Fine
Grasses and Sagebrush						
Prairie sandreed grass	Low	High	Low	Yes	Yes	No
Needle and thread grass	None	Medium	Low	Yes	Yes	No
Western wheatgrass	**High**	**High**	**Medium**	**No**	**Yes**	**Yes**
Blue grama grass	Medium	High	Medium	Yes	Yes	Yes
Little bluestem grass	None	High	Low	Yes	Yes	Yes
Big sagebrush	Low	High	Medium	No	Yes	No
Greasewood	High	High	Low	No	Yes	Yes
Bluebunch wheatgrass	Low	High	Low	Yes	Yes	Yes
Columbia needlegrass	Medium	None	Low	No	Yes	No
Trees						
Alpine fir	None	Low	Medium	Yes	Yes	No
Aspen	None	High	High	Yes	Yes	Yes
Ponderosa Pine	None	Low	Medium	Yes	Yes	No
Plains Cottonwood	**None**	**Medium**	**High**	**Yes**	**Yes**	**Yes**

Source: Compiled from the USDA PLANTS database, 2004.

ESTABLISHING A BASELINE AND MONITORING PROGRAM

Establishing a baseline study on the existing conditions of a site is a valuable method of identifying site-specific problems that can be mitigated prior to construction and operation of a CBNG impoundment. Once identified, appropriate design adjustments can be made to address the identified issues. Furthermore, baseline studies can also be used to reduce costs during the operations phase as many of the activities performed in a baseline study can be utilized in monitoring the site during operations.

Similar to a baseline study, monitoring activities can include surface and groundwater monitoring as well as monitoring for erosion, non-point source discharges, and/or evidence of potential dam failure.

Aspects of a baseline study that can be used in the site planning and design of proposed impoundments include: soils, bedrock, groundwater, and surface water. Planning for groundwater monitoring during the baseline study can ultimately reduce the overall costs of any monitoring program. Operational monitoring may also include monitoring the nearby surface water at the site, along with inspecting the site for erosion and non-point source discharges.

Soils Baseline

Regional soil data can be used for a preliminary assessment of the baseline for soils at a site. Properties such as clay percentage, percentage of soluble mineral assemblages, and cation exchange capacities can be reviewed for broad areas, but this data may not be uniformly available at the site specific level. Therefore, in addition to reviewing regional data, a site-specific soil investigation may need to be conducted for each impoundment. Soil borings can be installed in and around the proposed impoundment location to establish a better understanding of the existing soil conditions. By installing the soil borings in locations that can be completed into groundwater monitoring wells, savings of time and money can be realized during the planning phase of the project.

Water Well Drilling Rig Used To Install Monitoring Wells PRB, WY

Understanding the existing soil conditions, both at the surface and at depth, is important during impoundment siting and design. Soils analysis that includes soil salinity, soil K- factors, textures, slope, soil classification, Atterberg limits, location and extent of rock strata, and permeability can assist CBNG operators to determine the areas most suited for construction of an impoundment. The basic soil analyses listed above are important in assessing both geochemical and geotechnical soil conditions which are significant elements with respect the soils baseline in the planning and design phase for CBNG impoundments.

The physical collection of subsurface soils data will also provide opportunities to evaluate the nature and extent of the shallow bedrock geology which is critical in determining the ability of the underlying units to successfully accept infiltrating water from the impoundment. Three widely used and accepted methods for collecting soil samples and mapping shallow geology are: 1) drilling, 2) direct push technology (DPT), and 3) trenching. Drilling and DPT involve the creation of a soil boring and logging the soil column noted either in soil cuttings or in a thin sampling tube. Trenching generally involves visual observation and documentation of the stratigraphy of the trench walls. These methods are generally considered intrusive, as they require disturbance of the surface. Less intrusive indirect methods of mapping near surface bedrock conditions include: refraction seismic, ground magnets, direct-current resistivity, and transient electromagnetic. In addition to providing data relevant to bedrock conditions some of these applications are also useful in providing data about groundwater quality.

Through the use of soil sampling and geochemical analysis, one can determine the potential of the infiltrating water to leach minerals, salts, and metals out of subsoil. Samples from the soil borings can be collected from beneath the bed of the proposed impoundment and analyzed for calcium, magnesium, sodium, gypsum, manganese, carbonate, and bicarbonate. The potential for the infiltrating water to leach these constituents from the soil is dependant not only on the presence of the minerals in the soil, but also the quality of the produced water in the impoundment. The higher the quality of the produced water the more susceptible it is to leaching minerals from the soil as it infiltrates and saturates the existing vadose zone.

Geotechnical analysis of soil samples can help determine the suitability of the soil for foundation and abutments, any required foundation treatment, excavation slopes, and availability and characteristics of embankment materials (USACE, 1994). By understating the soil classification, physical properties, location and extent of rock strata, and groundwater piezometric levels, the operator can design the impoundment in such a way as to mitigate potential structural failures during operations.

Groundwater Baseline

The CBNG produced water that is discharged to an impoundment has the potential to interact with existing shallow groundwater aquifers. Because CBNG water quality may differ from the water quality of the shallow aquifer, it is important to establish a baseline for existing shallow aquifer water quality prior to construction. As previously noted soil borings can be strategically located so that they can also be completed as groundwater monitoring wells. Groundwater wells, lysimeters, or piezometers can be installed in such a way so that the potentiometric surface of the groundwater can be mapped and the direction of groundwater flow can be understood. Locations to consider for the installation of groundwater monitoring structures include: 1) “up-gradient” of the impoundment to establish the “background” quality of the groundwater during operations; 2) in/around the proposed dam location to identify foundation suitability as well as monitor the stability of the dam during construction; and 3) further “down gradient” from the impoundment, but upstream from any potential surface water discharge points to identify the existing water quality and monitor the impacts the infiltrating water has on the groundwater over time.

The operators considering installation of impoundments may want to consider the configuration of the monitoring locations if multiple monitoring structures are to be installed so as to maximize the data gathered. By understanding the quality of the existing groundwater and the direction in which the groundwater is flowing, the operator can realize benefits during the design and planning of an impoundment by including mitigation measures for potential problems that may become apparent.

Groundwater Monitoring

A groundwater monitoring program can be utilized to observe changes to the groundwater system and minimize the potential for negative impacts to groundwater from impoundment operations. The three primary components of a groundwater monitoring program are: 1) the number and location of monitoring wells, as established in the baseline study; 2) the identification of constituents and physical properties that may need to be monitored; and 3) the frequency that monitoring is conducted, which is typically driven by regulatory requirements. Table 3-7 lists common constituents and physical properties which can be included in a monitoring program.

Table 3-7: List of Potential Constituents and Physical Properties

Constituents and Physical Properties		
Arsenic (As)	Zinc (Zn)	Sulfate (SO_4)
Barium (Ba)	Copper (Cu)	Chloride (Cl)
Cadmium (Cd)	Boron (B)	Total Dissolved Solids (TDS)
Chromium (Cr)	Calcium (Ca)	Sodium Absorption Ratio (SAR)
Lead (Pb)	Sodium (Na)	pH
Selenium (Se)	Magnesium (Mg)	Temperature
Iron (Fe)	Manganese (Mn)	Specific Conductance
Potassium (K)	Fluoride (F)	

Surface Water Baseline

A baseline of the surface water quality can be coupled with the baseline groundwater quality to provide a better understanding of the potential interaction between surface water and the local groundwater system. In addition it may be beneficial to determine the baseline produced water quality in order to have an understanding of how the produced water will interact with the soil, groundwater, and surface water in the event that mixing occurs.

The baseline study of surface water bodies near a proposed impoundment can consist of a wide variety of activities that can include grab samples, continuous EC monitoring, flow rate monitoring, and ecological sampling. By establishing a baseline that spans the entire year, one can evaluate the natural changes (or lack of changes) to the surface water quality and assess later changes that may be attributed to CBNG operations. While it may not be feasible to collect surface water samples for a full year prior to impoundment operations, a single grab sample prior to operations is still valuable in determining the effects of CBNG production. In this instance, regional water quality sample data (such as that provided by USGS research projects) can be used to show how the water quality changes throughout the year. The seasonal trends displayed at the USGS gauging stations can supply valuable information about surface water flow and quality.

Benefits can be realized by establishing a baseline of the produced water quality and should be considered prior to placing an impoundment into operation. For example, the quality of the produced water may dictate whether the water can be used for irrigation, how it might interact with the soil as it infiltrates, and how it might react when mixed with surface and groundwater in a shallow aquifer.

Surface Water Monitoring

Surface water monitoring should be included with groundwater monitoring if there is evidence in the groundwater monitoring results that surface waters may be impacted. If evidence of groundwater impacts is seen in a nearby monitoring well, then consideration should be given to sampling the surface water down-gradient from the monitoring well. Furthermore, some discharges may be allowed over the spillway for on-channel impoundments during storm events, and if this occurs consideration should be given to monitoring surface water downstream from the discharge point. By monitoring the surface water and comparing results to the baseline study performed on the surface water, the impoundment operator may be able to reduce liability by showing that the CBNG produced water has had little to no impact on the surface water quality.

Once impoundment operations begin, surface water monitoring can be coupled with the groundwater monitoring program. If there is no evidence of migration in the groundwater monitoring program and there are no direct discharges during storm events or otherwise, then the monitoring of surface water systems may not be justifiable. Once the groundwater monitoring program shows evidence of the infiltration water migrating into the groundwater, then surface monitoring can be considered more closely. Monitoring frequency of the surface waters can coincide with the frequency of the groundwater and impoundment monitoring.

Monitoring of produced water at the impoundment can be performed at the impoundment to determine the extent to which the water chemistry changes due to exposure to the atmosphere and the materials of the impoundment. Research indicates that the exposure to the atmosphere and the oxygenation of the produced water alters the chemical composition of the water between a discharge point and the impoundment (Jackson, et al, 2003). The research indicated that pH and arsenic tended to increase from the time the water passes the discharge point to the time it spends in the impoundment, while barium tended to decrease over the same interval. The same list of constituents found in Table 3-7 can be used as a basis for determining what analyses to run on the water sample collected at the discharge point.

Erosion and Non-point Source Inspections

The operator of a CBNG impoundment can improve surface water quality by monitoring non-point source (NPS) pollution caused by erosion during the construction of the impoundment as well as during CBNG operations. During construction one of several industry accepted erosion control Best Management Practices (BMPs), such as silt fences or hay berms, could be utilized to prevent erosion of soils during storm events. The effectiveness of the erosion control devices used can be inspected after rainfall events greater than 0.5” to ensure they are structurally sound and working properly. Any areas that are not working properly can be fixed to prevent future problems.

Impoundment Inspections

Savings in overall project cost can be realized by monitoring the impoundment (or series of impoundments) for minor problems caused by various events, such as erosion from rainfall or growth of unwanted vegetation in the dam, and correcting these minor problems through routine maintenance versus correcting the major problems that arise when a structure experiences an untimely breach. Table 3-8 provides a summary of what can be done to mitigate minor problems that are observed during a site inspection before they become major problems.

The frequency of the dam inspection can be dependant on the nature of the site, the number of dams, and the size of the structure. Annual inspections may be deemed sufficient; however, the results of annual inspections may be reviewed and deemed that semi-annual or bi-annual is more appropriate.

Table 3-8: Impoundment Inspection Potential Mitigation Measures

Earthen Dam Inspection • Remove trees and woody vegetation • Remove/trap burrowing animals • Re-seed and repair bare areas or gullies • Repair holes, depressions, and/or cracks • Repair seepage, leakage, and/or “piping”	Principle Spillway Inspection • Remove trash and/or debris from trash rack • Clear obstructed water quality orifice(s) • Repair leaking and/or damaged riser/barrel • Repair leaking and/or damaged concrete spillway • Repair eroded or blocked outlet pipe • Replace or unclog filter gravel around riser.
Emergency Spillway Inspection • Remove trees and woody vegetation • Re-seed and repair bare areas or gullies • Replace or repair displaced rip-rap • Remove obstructions from spillway	General Maintenance Inspection • Repair eroded inlet channel • Re-seed and/or repair bare areas or gullies • Replace or repair rip-rap at discharge pipe(s) • Remove trash and/or debris from pond area

Observed Impacts to Groundwater Resulting from the Operation of CBNG Impoundments

INTRODUCTION

The field study was performed in two different surface watershed areas in which there are numerous on-going CBNG operations. These areas include the Prairie Dog Creek Drainage (which is approximately 15 miles from Sheridan, Wyoming), and LX Bar Creek Drainage (which is approximately 35 miles from Gillette, Wyoming). Impoundment availability was one of the primary factors for choosing these locations as numerous impoundments exist in these areas.

An additional consideration in choosing these areas were previous research performed by the U.S. Department of Energy related to remote sensing flyovers conducted over the Prairie Dog Creek and LX Bar Creek drainages. These remote sensing flyovers were conducted using a “frequency-domain sensor” tool suspended from a helicopter. The purpose of the flyover deployment was an effort to develop a methodology for gathering indirect groundwater flow data that could be used to assist in the various analyses associated with energy development projects in the PRB. The aerial data is supplemented with detailed ground-level or subsurface data which can help to correlate the spatial flyover data. This research project provides some of the subsurface data for that project with detailed subsurface geophysical logging of the installed boreholes.

ALL Consulting and the WDEQ identified more than 20 impoundment sites as potential investigation locations. Through a combined effort of identifying similarities and differences between the various impoundments and field reconnaissance of the potential sites for drilling rig access, the researchers were able to narrow the listing of potential study sites to ten impoundments. Eight of these sites were finally chosen for investigation and had monitoring wells installed during the summer of 2006. Each of the impoundments considered for study had been receiving CBNG produced water since at least 2002, with some having been in operation prior to 2002. The identified impoundments include both on-channel and off-channel construction and are located over a variety of terrain and soils. Site location maps of the impoundment locations that were studied during the summer of 2006 are attached as Figure 4-1 and Figure 4-2 (Appendix A).

INVESTIGATION METHODS

This section describes background information on the operational guidelines and procedures documents that were developed for field data acquisition activities associated with the groundwater evaluation at the CBNG impoundment locations. All of the specific procedures were detailed in a Standard Operating

Procedures (SOP) manual that covered all tasks necessary to successfully complete the field effort. The Quality Assurance Project Plan (QAPP) provided the guidelines, specifications, and detailed lists regarding laboratory analyses and reporting of chemical data for this project. There was considerable effort invested by the researchers to ensure that the methods identified in the SOP and QAPP documents produced quality data for analysis that would withstand the scrutiny of state and federal guidelines as well as non-governmental organizational review. ALL Consulting and the WDEQ reviewed and utilized information and methods from other highly scrutinized work plans including plans which were used for field investigations at RCRA and CERCLA sites. The data collection methods identified in the SOP documents developed for this project, are standard practices used by the hazardous waste investigation industry. In addition to these data protocol documents a Health and Safety Plan was also developed for the project and all field personnel were required to read and become familiar with that document prior to commencing actual field operations.

As the strategy for the investigation at the CBNG impoundments located in the Wyoming portion of the PRB was to establish a groundwater monitoring system of the upper most groundwater bearing zone at each of the impoundment sites, the field activities required to complete this part of the project included hollow-stem augering and/or air rotary drilling of boreholes, the installation of monitoring wells, and groundwater sampling activities. All of these major activities and sub-tasks associated with them were covered in the SOP and QAPP documents.

Site Reconnaissance and Study Sites

Site reconnaissance was conducted in the fall of 2005 to evaluate potential sites for access, to confirm the size of the impoundment, and to assess both the topography and the apparent direction of unconfined groundwater flow. Reconnaissance was conducted by personnel from ALL Consulting, the WDEQ, CBNG operators, and landowners. The impoundments identified during reconnaissance are listed on Table 4-1. At the time of site reconnaissance, all of the potential study sites had been receiving CBNG water for at least three years.

Three of the impoundments chosen for investigation are located in the Prairie Dog Creek Drainage and are situated north of Sheridan in Sheridan County, Wyoming (See Figure 4-1, in Appendix A). These impoundments are operated by the J.M Huber Corporation and vary in capacity from 20 acre-feet to almost 50 acre-feet. Two of these impoundments are classified as on-channel impoundments (Sandy and Joe Draw Jr.) and one is classified as off-channel (Lori).

The other seven impoundments considered for investigation are located in the LX Bar Creek Drainage and are situated northeast of Arvada in Campbell County, Wyoming. Operators for these impoundments include the J.M Huber Corporation, Yates Petroleum and Termo Resources. Three of these impoundments are classified as on-channel (Ancient Warrior, Golden Eagle, and Horseshoe Stock Reservoir). The other four impoundments (Yates State #1, Waylon, Bounty Hunter, and Upper Termo Ranch) are all classified as off-channel. The five impoundments located in the LX Bar Creek watershed which were ultimately chosen for investigation included the Golden Eagle, Yates State #1, Bounty Hunter, Upper Termo Ranch, and Waylon impoundments (See Figure 4-2, in Appendix A).

Drilling below an On-Channel CBNG Impoundment in the Prairie Dog Creek Watershed, Wyoming

Table 4-1: Summary of Impoundments Investigated during the 2006 Field Season.

Reservoir Name	Qtr	Sect	TWN	RNG	Monitoring Wells	DOE Boreholes	Name as Listed on SEO Permit	SEO Permit #	Capacity (SEO Permits) ac-feet	Year SEO Permit Issued	Operator Name	WPDES Permit #
Prairie Dog Creek Reservoirs												
Lori	SWNW	36	58	83	4 *	3	Lori Reservoir	P11137R	39.08	2001	Jim Huber Corporation	WY0046558-003
Joe Draw Jr.	NENW	3	57	83	3	none	Joe Draw Jr. Reservoir	P11106R	23.475	2000	Jim Huber Corporation	WY0040568-003
Sandy	SWSW	34	58	83	3	3	Sandy Stock Reservoir	P17735S	19.99	2001	Jim Huber Corporation	WY0040568-020
LX Bar Creek Reservoirs												
Golden Eagle	C NE	26	56	75	3	3	Golden Eagle Reservoir	P11077R	29.82	2000	J. M. Huber	WY0040347
Yates State #1	NENW	16	56	75	2	none	Kline Draw #1	P14310S	18.46	2001	Yates	WY0046451
Bounty Hunter	SWNE	22	56	75	3	3	Bounty Hunter Stock Reservoir	P14645S	13.41	2001	Yates	WY0046892
Upper Termo Ranch	SENW	15	56	75	3	none	Miller Stock Reservoir	P15007S	15.69	2002	Termo	WY0054917
Waylon	SENW	9	56	75	3	none	Waylon Stock Reservoir	P14856S	19.6	2002	Yates	WY0046892
Yates State #2	*SWSW*	*16*	*56*	*75*	*none*	*none*	*Kline Draw #7*	*P14330S*	*9.95*	*2001*	*Yates*	*WY0046451*
Ancient Warrior	*NENE*	*26*	*56*	*75*	*none*	*none*	*Ancient Warrior*	*P14129S*	*3.99*	*2000*	*J. M. Huber*	*WY0040347*

* includes one DOE borehole that was completed as a monitoring well.

Italics' indicate an impoundment that was considered but not investigated.

THIS PAGE INTENTIONALLY LEFT BLANK

Drilling Methods, Soil Borings, and Soil Samples

After site reconnaissance was completed, the location for each of the initial soil borings/monitoring wells at each of the eight impoundments was located by field representatives of ALL Consulting and the WDEQ. Borehole/well locations were cleared for the presence of underground utilities prior to initiation of drilling activities. Soil borings were completed using a combination of hollow-stem auger (HSA) and air rotary drilling methods. The initial soil boring at each of the Prairie Dog Creek impoundment sites were drilled using HSA drilling techniques until auger refusal. From these initial HSA drilled soil borings, soil samples were collected with a two foot split spoon sample hammered before the augers were advanced. The depths of soil boring samples were marked on the borehole lithologic logs and well construction diagrams for each soil boring completed (See Appendix B). The soil cores were removed from the samplers, measured for length of recovery, and a project geologist described the lithology using the Unified Soil Classification System (USCS). From each of the split spoon samples, a minimum of two soil samples were collected for analysis by the USGS. Soil samples measuring approximately six inches (6”) were collected from the top and bottom of the recoverable section from the split spoon. Each sample was placed in a stainless steel container provided by the USGS and the lid of each container was sealed using electrical tape. On top of each sample container, a label was created which noted the sample ID, date and time of sampling, and depth interval from which each sample was collected. The results from this soil sampling will be reported at later date by the USGS.

The number of monitoring wells that were installed at each impoundment was determined by the project team in the field, and was limited to a maximum of four and a minimum of two at each impoundment if groundwater was encountered at or above a depth of 150 ft below ground surface. One borehole at each impoundment was cored (2 feet core barrel collect once every 5 feet) through the vadose zone to allow for a complete collection of soil samples; the depth of this coring was based on site-specific conditions (depth to bedrock or core barrel refusal).

The initial well/borehole at each impoundment site was placed on the apparent down-gradient side of the impoundment. Proximity to the impoundment varied at each location and was determined by the geologist(s) in the field. Subject to drilling rig access the initial well/borehole locations were generally located within 100 ft of the impoundment. A second well/borehole was placed at the apparent up-gradient side of the impoundment and the upper vadose zone of that borehole was cored as previously described. At the field geologist(s) discretion, a third and/or fourth well was installed to attempt to determine the lateral extent of infiltrated water, and direction of groundwater flow when it appeared that the groundwater surface was not reflective of the surface topography. Decisions related to the installation of additional monitoring wells were based on observed site and borehole geologic conditions, or other site-specific field parameters.

Air Rotary Drilling Boreholes and Monitoring Wells at CBNG Impoundments PRB, Wyoming

For those soil borings in which groundwater was not reached prior to the refusal of the HSA, the drilling rig was switch over to air rotary drilling operations to allow for the continued drilling until groundwater was reached. Air rotary drilling techniques facilitate the identification of first groundwater because lithologic cuttings are generally not returned after groundwater is encountered. Once groundwater was encountered the borings were cleaned out by surging air down the borehole to remove cuttings prior to beginning monitoring well installation. If groundwater was encountered within 150 ft of the surface, the borehole was then completed as a monitor well.

In addition to the above mentioned monitor wells, twelve drilling locations were drilled based on specific geophysical signatures observed as part of an ancillary research project being conducted by the Department of Energy. These twelve locations were drilled, soil samples obtained, and where appropriate were completed as monitoring well locations to support this groundwater investigation. The twelve borehole locations are shown on Figure 4-1 and Figure 4-2 (Appendix A).

Monitoring Well Installation

All monitoring wells were installed using a combination of hollow stem auger and air-rotary drilling techniques. The depth of each monitoring well was determined in the field based on the depth at which the first groundwater was encountered. All monitoring wells were constructed of 2-inch diameter minimum polyvinyl chloride (PVC) casing. From five to 20 ft of 0.020-inch slotted screen with a 1 foot sump below the screen was set at an appropriate interval in each well. A filter pack of 10/20 silica sand was placed in the annulus around the screen and at least two feet above the screened interval. A 2 foot seal of sodium bentonite pellets/chips was placed above the filter pack. The remainder of the annulus was grouted with a bentonite/cement grout. The monitoring wells were completed at the surface with a 3 foot x 3 foot concrete pad and an outer protective casing. Flush- mount pads were installed in areas of high traffic.

Well construction diagrams were completed for each monitor well and are present in Appendix B. The on-site geologist observed the entire well installation process for each well to ensure that procedures were completed in accordance with the SOP manual. Surface completion of the wells included a locking cap on a steel protective casing anchored in concrete. Well completions utilized were consistent with Chapter 11 of the Wyoming Water Quality Rules and Regulations.

Monitoring Well Development

The development of all monitoring wells completed under this project was commenced after the concrete well pad had been poured and allowed sufficient time to cure. Well development was performed using bailers, down-hole submersible pumps, and air lift techniques. Development with bailers was performed by initially surging the well. The surging was preformed in order to facilitate the setting of the filter pack around the well screen. After the initial surging, a minimum of five volumes of water within the well casing and the filter pack were removed by bailing or air purging techniques. Water quality parameters (pH, specific conductance, temperature and turbidity) were recorded after each well volume was removed. After five volumes were removed and pH, specific conductance and temperature had stabilized, development was determined to be complete. In some instances when turbidity levels remained high (in some cases above 50 standard units), field personnel had to determine if additional development was necessary.

Groundwater Sampling

All monitoring wells were sufficiently purged prior to groundwater sampling activities. Purging was required to remove the stagnant water from the well and assure that a representative sample was obtained.

Low flow sampling procedures per the requirements of the SOP manual were used for sample collection. Water quality parameters (pH, specific conductance, and temperature) were recorded after each well volume was removed. After three volumes or more were removed and pH, specific conductance, and temperature were stabilized, sampling commenced. The prescribed water quality measurements were taken just prior to sampling for a final water quality reading. If the well went dry prior to the removal of three well volumes, the well was allowed to sit overnight and sampled within 24 hours of the time it was bailed.

Groundwater sampling activities were performed consistent with the project SOP and with the Wyoming Department of Environmental Quality –Water Quality Division's "Compliance Monitoring for Ground Water Protection Beneath Unlined Coalbed Methane Produced Water Impoundments" (WDEQ, 2004) and "Groundwater Sampling for Metals: Summary" (WDEQ, 2005).

STUDY SITES SUMMARY

The following sections discuss the general geologic and hydrogeologic conditions found at certain existing and previously sampled CBNG impoundment sites operated by Marathon Oil Company located near Arvada, Wyoming as well as detailed descriptions of the eight impoundments investigated under this research effort during 2006.

Geology of the Arvada Area

The CBNG infiltration impoundments operated by Marathon Oil Company in the Arvada area are located along the alluvial terraces of the Powder River. The U.S. Geological Survey has identified three relatively well defined terraces near Arvada; these include from oldest to youngest the Kaycee, the Moorcroft, and the Lightning (Leoopold and Miller, 1954). These terraces are situated above the Fort Union formation bedrock, which in the area varies in lithologic character from conglomerate, sandstone, siltstone, and mudstone to carbonaceous shale. Boreholes drilled through these alluvium terrace deposits encountered weathered, gray shale at depths between 15 to 39 feet below the terrace outcrop (CBM Associates, 2003). The alluvium deposits are a mix of silt and fine-grained sands with lenses of coarser sands and gravels.

Marathon operated a total of nine infiltration impoundments completed above alluvial aquifers (primarily the Lightning Terrace) in the Arvada, Wyoming area that were studied at this project. Water quality data gathered from aquifers located below these impoundments were analyzed and submitted to the WDEQ by the operator (Marathon Oil Company) in 2001 through 2005. These data submittals by the operator were submitted under both a voluntary arrangement with the WDEQ and in partial fulfillment of requirements under the state permit monitoring and compliance program. The eight impoundments that were covered under this data submittal included the Jeff 3, Jeff 5, Jeff 6, Jeff 7, Arvada Phil's Pond, Arvada Cottonwood 8, Arvada Santiago, and Arvada Tietjen impoundments (See Figure 4-3, Appendix A).

Prairie Dog Creek Area

The Prairie Dog Creek (PDC) watershed sub-basin is located within the Upper Tongue River drainage and is situated east of the City of Sheridan in Sheridan County, Wyoming. The PDC area has undergone CBNG development over the course of the last 10 years. Three impoundment study sites are located within the Prairie Dog Creek Watershed; the Lori, Sandy and Joe Draw Jr. impoundments.

Lori Impoundment

The Lori impoundment is located in the SW ¼ of the NW ¼ of Section 36 T58N R83W and has a capacity of 6.23 acre-feet. The impoundment has been used to hold CBM produced water for six years. The Lori impoundment is classified as an off-channel impoundment set above un-named minor tributary of Prairie Dog Creek (Figure 4-4, Appendix A). In 2006 a total of seven boreholes were drilled at the Lori site. Four of the boreholes (Lori MW-1 through MW-4) were drilled in a down-gradient position with one borehole being abandoned (MW-2) and three boreholes (PD-1, PD-2, and PD-3) drilled in an up-gradient position (See Figure 4-4, Appendix A). The down-gradient borings and wells were drilled to define the shallow geology and to determine if there were impacts to groundwater as a result of infiltrating water from the impoundment. The up-gradient borings and wells were drilled to provide background groundwater quality data, and in support of the ancillary DOE groundwater flow study and were logged using wire-line borehole geophysical tools. The boring logs and well construction diagrams for all boreholes at the Lori impoundment are included in Appendix B. Table 4-2 provides a summary of borehole and monitoring well completion data for borings near the Lori impoundment.

Area Geology - Lori Impoundment

This geologic interpretation of the area near the Lori impoundment was developed from analysis of the data collected from boreholes completed as part of the field effort in 2006 (Appendix B), wire-line logs from several nearby CBNG wells, and geophysical logs (Appendix B) that were collected after the completion of the borings drilled near the Lori impoundment. The wire-line logs of several CBNG wells in the vicinity of the Lori impoundment were examined to discern the shallow subsurface coal geology for the immediate area. The shallowest coal seam in the area, the Taft Coal seam, occurs less than 200 ft bgs but does not appear to be consistent over the area. The Smith Coal seam occurs at a depth of approximately 250 ft bgs, and appears to be relatively consistent over the area exhibiting minor structural dip to the east (See Figure 4-4, Appendix A). Neither the Taft nor the Smith coal seams were identified in the shallow borings or monitoring wells drilled as part of this project (boring logs are presented in Appendix B). The Roland-Baker, a ten-foot coal seam, which appears at a depth of less than 100 ft bgs over the northern portion of the area, was penetrated in some of the Lori impoundment monitoring wells (See Cross Section 4-1, in Appendix C).

The location of Cross Section 4-1 (Appendix C) is show on the map in Figure 4-4 (Appendix A) as depicted by the line A-A'. Cross Section 4-1 shows the variable geology that exists in the shallow subsurface area just to the west of Lori impoundment. The upper shallow zone is primarily clays and silts from the upper area near PD-1 down the slope to the bottom area below the Lori impoundment near MW-3 and MW-4. Underlying this zone is an approximately 5 ft thick dry sand zone that is not consistent across the site and appears to have been eroded away in the area near MW-4 as shown in Cross Section 4-1. Below this sand zone to the south is a claystone that appears to pinch out to the north in the area of PD-1 and is replaced by a coal seam which extends southward, thinning considerably in the area of MW-3 and MW-4. This coal seam, which is interpreted to be the Squirrel coal seam, was interpreted to be the source of water for the monitoring wells MW-3, MW-4, and PD-1.

Table 4-2: Summary of Borehole and Monitoring Well Completion Information at the Lori Impoundment

Name	Gradient Position	Dist. From Impound.	Elev.	Depth to SWL	Elev. SWL	Depth to Bedrock	Lithology of the Water Zone	TD	Elev. at TD	Screen	Elev. of Screened Interval	Comments
Lori MW-1	Down	260	3561	30.61	3530	25	Siltstone	40	3521	18-38	3523-3543	Well purged with little or no draw down @ 1-2 gpm (E.C. =3,200 µmhos/cm)
Lori MW-2	Down							109				Hole collapsed. Borehole plugged and abandoned.
Lori MW-3	Down	315	3554	35.55	3518	21	Coal and Claystone	44	3510	34-44	3410-3520	No split spoon sampling. (E.C. =2,000 µmhos/cm)
Lori MW-4	Down	440	3558	31.63	3522	14	Coals and Claystone	44	3514	33-43	3514-3524	Well yielded .5 to 1 gpm on airlift. (E.C. =3,000 µmhos/cm)
PD-1	Up	575	3600	72.1	3528[1]		Sandstone and Coal	121	3479	71-90	3510-3529	Plugged back with bentonite chips. (E.C. =3,000 µmhos/cm)
PD-2	Up	~575	3607	74	3533[1]			120				No returns from zone with water flow. Borehole not completed for monitoring
PD-3	Up	~575	3612	79	3533[1]	15	Siltstone, Sandstone and Coal	89				Coal logged @ 15' interpreted to be Roland-Baker. Coal logged @ 84' interpreted to be the Squirrel Coal seam. Borehole not completed for monitoring

1. Static water level (SWL)elevations are based on depth to water encountered during drilling of the borehole.
Note: Measurements are all in feet

Summary of Local Geology and Hydrogeology Conditions: Lori Impoundment

The geology proximal to the Lori impoundment appears to be relatively consistent with overburden soils and alluvial sediments lying above bedrock which is present at depths from 14 to 25 ft bgs. In the vicinity of the up-gradient borings, bedrock is present at depths of 15 to 18 ft bgs. Bedrock is composed primarily of claystones and siltstones with lesser inter-bedded fine-grained sandstone. Minor coal seam horizons are also present. The uppermost correlative coal of significance was interpreted to be the Roland-Baker Coal seam, which was encountered at a depth of 15 ft bgs in the Prairie Dog-3 boring. However, this shallow coal was not observed in any of the other borings. A lower coal which is believed to correlate with the Squirrel Coal seam is present in the Prairie Dog-1 and Prairie Dog-2 borings, and possibly at the bottom of the Prairie Dog-3 boring at depths ranging from 68 to 89 ft bgs. This coal appears to be correlative to the coal seam present at depths of 29 to 37.5 ft bgs in the Lori MW-3 and Lori MW-4 wells. A calculation of apparent dip for this lower coal indicates a local dip of 66.74° towards the northeast (See calculations in Appendix D).

The water table observed at the Lori MW-3 and MW-4 within the coals bed appears to correlate with the groundwater encountered in sandstone and coal bed at the Prairie Dog-1 and Prairie Dog-3 locations at depths of 69 and 79 ft bgs, respectively. This interpretation is based on the elevations of the screen intervals and the static water level elevations (see Cross Section 4-1). Groundwater is also present at Lori MW-1 well in a siltstone at depth of 24.9 ft bgs. The groundwater in MW-1 may correlate to that encountered in the coal seams in MW-3 an MW-4 and the sandstone/coal seam found in the Prairie Dog-1 monitoring well. Mapping of measured static water levels indicates that within the coal stringer aquifer for this area the groundwater flows towards the southeast at a dip of 87.69° with an estimated hydraulic gradient of 24.82 feet/feet likely indicating a local mounding affect and within the siltstone aquifer groundwater flow is towards the southwest at a dip of 4.96° an estimated hydraulic gradient of 0.087 feet/feet (See calculations in Appendix D).

Sandy Impoundment

The Sandy impoundment is located in the SE ¼ of the SE ¼ of Section 33 T58N R83W. The impoundment has a capacity of 19.99 acre-feet and has been used to hold CBNG produced water for 6 years. The impoundment has been classified as an on-channel impoundment in the State records, as it is set into the upper portion of an un-named tributary of Prairie Dog Creek. The sides of the draw on which the impoundment is located are relatively open in the up-gradient direction and relatively steep in the down-gradient. The elevation of the water level is approximately 3,620 ft amsl. In 2006 a total of six boreholes were drilled at the Sandy impoundment site (Figure 4-5, Appendix A). Two of the boreholes (Sandy MW-2 and Sandy MW-3) were drilled in a down-gradient position relative to the impoundment and one borehole was drilled in an up-gradient position (Sandy MW-1). Three boreholes (PD-4, PD-5, and PD-6) were drilled cross-gradient of the impoundment (Figure 4-5, Appendix A). The down-gradient borings and wells were drilled to define the shallow geology and to determine if there were impacts to groundwater as a result of infiltrating water from the impoundment. The up-gradient well and cross gradient borings were drilled to provide background groundwater quality data, and in support of the ancillary DOE groundwater flow study and were logged using wire-line borehole geophysical tools. The boring logs and well construction diagrams for all boreholes at the Sandy impoundment are included in Appendix B. Table 4-3 provides a summary of borehole and monitoring well completion data for borings near the Sandy impoundment.

Area Geology - Sandy Impoundment

This geologic interpretation of the area near the Sandy impoundment was developed from analysis of the data collected from boreholes completed as part of the field effort in 2006 (Appendix B), wire-line logs from several nearby CBNG wells, and geophysical logs (Appendix B) that were collected after the completion of the borings drilled near the Sandy impoundment. Two coal seams were observed on the CBNG logs – the Upper Roland, also called Baker-R, and the Lower Roland, also called Baker-T or Taft. The Lower Roland appears in several of the boreholes (Cross Section 4-2). The thin Upper Roland has apparently not been identified in outcrop in the area. The Upper Roland Structure Map is shown in Figure 4-5. This map shows that Upper Roland Coal exhibits dip from west to east across the area. This coal dips at a rate of approximately 150 feet per mile (~3% dip) but in the vicinity to the impoundment it appears to be rather flat-lying with little apparent dip.

The location of Cross Section 4-2 (Appendix C) is show on the map in Figure 4-5 (Appendix A) as depicted by the line A-A'. Cross Section 4-2 shows the variable geology that exists in the shallow subsurface near the Sandy impoundment. The shallowest near-surface area is primarily clays and silts from the upper area near MW-1 down the slope to the bottom area below the Sandy impoundment near MW-2.

THIS PAGE INTENTIONALLY LEFT BLANK

Table 4-3: Summary of Borehole and Monitoring Well Completion Information at the Sandy Impoundment

Name	Gradient Position	Distance From Impound	Elev.	Depth to SWL	Elev. SWL	Depth to Bedrock	Lithology of the Water Zone	TD	Elev. at TD	Screen	Elev. of Screened Interval	Comments
Sandy MW-1	Up	150	3673	91.5	3582		Coal	113	3560	93-113	3560-3580	Water zone interpreted to be in the Upper Roland Coal Seam
Sandy MW-2	Down	250	3616	59.6	3556		Coal	106	3510	81-101	3515-3535	Water zone interpreted to be in the Upper Roland Coal Seam. Approximate shallow silt aquifer SWL @ 26' on backside of well casing prior to final completion
Sandy MW-3	Down	50	3623	17.69	3605	18	Alluvial Silt	25	3598	15-25	3598-3608	Water zone interpreted to be Quaternary / Holocene alluvial silt deposits. Low grade coal bed @ 18' bgs
PD-4	Cross	1,000	3637				Coal	122	3515			Water zone interpreted to be in the Upper Roland Coal Seam. No SWL taken. Borehole not completed for monitoring.
PD-5	Cross	~1,000	3640	59	3581		Coal	120	3520			Water zone interpreted to be in the Upper Roland Coal Seam. Borehole not completed for monitoring
PD-6	Cross	~1,000	3638	72	3566		Coal	120	3518			Water zone interpreted to be in the Upper Roland Coal Seam. Borehole not completed for monitoring

Note: Measurements are all in feet

Underlying this zone is a thin coal seam that is not consistent across the site and appears to have been eroded in the area near the current stream valley or pinches out in this area as shown in Cross Section 4-2. Below this coal are several other thin pinching coal seams in the area above the impoundment near MW-1, while below the impoundment near MW-2, there is nearly 70 ft of siltstone and claystones. The next major coal seam encountered at MW-1 and MW-2 is interpreted to be the Upper Roland Coal which is present at a shallower depth near MW-1 and approximately 20 ft lower at MW-2. Across the stream valley near PD-4, PD-5, and PD-6, another thin shallow coal was identified at approximately 20 ft below land surface thinning to the east from PD-4 to PD-6 (Cross Section 4-2). Below this coal is a series of inter-bedded claystone and siltstones for about 60 ft until the next thick coal seam is encountered. This coal seam is interpreted to be the Upper Roland coal seam as was seen in the monitoring wells MW-1, and MW-2 (see Cross Section 4-2).

Summary of Local Geology and Hydrogeology Conditions: Sandy Impoundment

The geology of the shallow subsurface materials near the Sandy impoundment is relatively consistent with overburden soils and alluvial sediments lying above bedrock which is present at an approximate depth from 8 to 25 ft bgs. In the vicinity of the DOE borings, bedrock is at or very near the land surface. The bedrock lithology is composed primarily of claystones with lesser amounts of inter-bedded siltstone and fine-grained sandstone. Minor coal horizons, typically low-grade lignite, are also present. The uppermost correlative coal of significance is the Upper Roland Coal seam which typically occurs from 75 to 113 ft bgs and attains a thickness estimated at 9 ft to greater than 10 ft (see Cross Section 4-2). Mapping the top of this coal indicates a strong dip towards the east (Figure 4-5). The Upper Roland Coal seam appears to be the uppermost continuous water bearing zone directly underlying the Sandy impoundment and is interpreted to be present at ~60 ft below the reservoir's bottom. A shallower water lens exists under the surface drainage channel as identified in the boring for MW-3. This zone is present within the alluvial overburden and it may also partially underlie the impoundment. This is supported by what was interpreted to be an apparent groundwater seep located approximately 100 ft down the drainage channel from MW-3 in an erosional head-cut of the surface drainage feature in which MW-3 is drilled. Water from this seep was observed to extend down the drainage feature for approximately 2,000 ft. The static water level observed at 26 ft below top of casing (btc) in Sandy MW-2 (See Table 4-3) is interpreted to be correlative with the shallow alluvial aquifer encountered in MW-3 and the observed head-cut seep. Water samples were not collected from the groundwater observed outside the casing of MW-2 or from the head cut seep. Analysis of measured static water levels indicates that groundwater within the Upper Roland Coal dips at 8.36° southeast with an estimated hydraulic gradient of 0.147 feet/feet (See calculations in Appendix D).

Joe Draw Jr. Impoundment

The Joe Draw Jr. impoundment is located in the SW ¼ of the SE ¼ of Section 35 T58N R83W. The impoundment reservoir has a capacity of 19.6 acre-feet and has contained CBNG produced water for 6 years. The sides of the adjacent draw are relatively steep and narrow up-gradient of the reservoir and relatively wide and open down-gradient of the reservoir. The Joe Draw Jr. impoundment is classified as an off-channel impoundment set above the alluvium of Prairie Dog Creek and between the valleys of Joe Draw Creek and an un-named creek to the south-west. The impoundment reservoir surface is at approximately 3,600 ft amsl. In 2006, two boreholes (Joe Draw Jr. MW-1 and Joe Draw Jr. MW-2) were drilled down-gradient of the impoundment, and one borehole was drilled up-gradient of the impoundment (Joe Draw Jr MW-3) as shown on Figure 4-6 (Appendix A). The three wells were drilled to define the shallow geology, to determine if there were impacts to groundwater as a result of infiltrating water from the impoundment, and to provide background water quality data. The boring logs and well construction diagrams for all boreholes at the Joe Draw Jr. impoundment are included in Appendix B. Table 4-4 provides a summary of borehole and monitoring well completion data for borings near the Joe Draw Jr. impoundment.

Area Geology - Joe Draw Jr. Impoundment

This geologic interpretation of the area near the Lori impoundment was developed from analysis of the data collected from boreholes completed as part of the field effort in 2006 (Appendix B), wire-line logs from several nearby CBNG wells, and geophysical logs (Appendix B) that were collected after the completion of the borings drilled near the Joe Draw Jr. impoundment. Locally, the shallowest coal seam is the Squirrel seam, which occurs at approximately the level of the impoundment on the plateau to the east of the Joe Draw Jr. impoundment (see Cross-Section 4-3). The Squirrel seam is interpreted to be the same coal that is seen in outcrop near the high-water mark of the reservoir. The next shallowest and most consistent coal is the Baker-R that occurs in the area of the CBNG wells at about 150 ft bgs. This appears to be the coal seam seen at approximately 105 feet bgs in the Joe Draw Jr. MW-3. The Baker-R appears to sub-crop beneath the alluvium under Prairie Dog Creek to the northwest of Joe Draw Jr. MW-2. The included structure map contoured on the top of Baker-T coal, which is located below the Baker-R coal, and shows dip to the northeast (See Figure 4-6).

The location of Cross Section 4-3 (Appendix C) is show on the map in Figure 4-6 (Appendix A) as depicted by the line A-A’. Cross Section 4-3 shows the variable geology that exists in the subsurface near the Joe Draw Jr. impoundment. The shallow near surface area is comprised of bedded clays and sands from the upper area near MW-3 down the slope to the bottom area below the Joe Draw Jr. impoundment near MW-1 and MW-2 (Cross Section 4-3). Underlying this zone in the upland areas is a coal seam that appears to have outcrop in the area of the impoundment. Below this coal are inter-bedded sands, siltstones and claystones down to about 3,830 ft where two consistent coal beds interpreted to be the Baker-R coal are present as seen in Cross Section 4-3. Below this coal is a series of inter-bedded claystone and siltstones of approximately 50 ft in thickness across all three MW locations. The bottom of this siltstone zone is source of groundwater for all three monitoring wells and based on water chemistry (see discussion in Appendix D), this siltstone is interpreted to be in hydrologic connection with a coal seam.

Table 4-4: Summary of Borehole and Monitoring Well Completion Information at the Joe Draw Jr. Impoundment

Name	Gradient Position	Dist. From Impound.	Elev.	Depth to SWL	Elev. SWL	Depth to Bedrock	Lithology of the Water Zone	TD	Elev. at TD	Screen	Elev. of Screened Interval	Comments
Joe Draw Jr. MW-1	Down	120	3579	78.31	3500	5	Siltstone	105	3474	85-105	3474-3494	Minor showing of water in Claystone (30-31') & Baker-R Coal (41-43'). Approximate SWL for Claystone / Baker –R Coal @ 33' (3544) on backside of well casing prior to final completion.
Joe Draw Jr. MW-2	Down	350	3568	67.13	3501	22	Siltstone	92	3476	72-92	3476-3496	Baker –R Coal (24-27') & (34-39') bgs. Baker-T Coal not reached.
Joe Draw Jr. MW-3	Up	300	3633	103.4	3530	15	Siltstone	167	3466	147-167	3466-3486	Baker –R Coal (100-105') & (111-115') bgs.

Note: Measurements are all in feet

Summary of Local Geology and Hydrogeology Conditions: Joe Draw Jr. Impoundment

The geology proximal to the Joe Draw Jr. impoundment appears to be relatively consistent with overburden soils and alluvial sediments lying above the bedrock, which is present at depths of 5 to 22 ft bgs. The bedrock is composed primarily of siltstones and claystones. Coal seams are present at two primary horizons: the Baker-R coal and the Baker-T. Mapping the top of the Baker-T coal (see Figure 4-6) indicates a local dip towards the northeast. The siltstone underlying the Baker-R seam is the uppermost continuous water bearing zone beneath the Joe Draw Jr. reservoir. Shallower perched water lenses of probable isolated horizontal extent may also be present. These zones are equivalent to or lie above the Baker-R coal. In the vicinity of the reservoir, structural dip appears to be to the northeast. This would carry any infiltrate toward the Joe Draw Creek, although the alluvium does not appear to cut into the siltstone aquifer.

All of the three Joe Draw Jr. monitoring wells are screened in a bedrock siltstone aquifer between the Baker-R and the Baker-T coal seams. None of these three wells appear to be located at a structural position below that of the impoundment. Analysis of measured static water levels indicates that, within the siltstone aquifer, groundwater flows towards the northeast at a dip of 3.40° with an estimated hydraulic gradient of 0.059 feet/feet (See calculations in Appendix D).

LX Bar Creek Geology

The LX Bar Creek watershed is located within Campbell County, Wyoming, and is situated near the town of Spotted Horse, Wyoming, approximately 20 miles northwest of Gillette. The LX Bar Creek area has undergone CBNG development over the course of the last several years. LX Bar Creek is an ephemeral drainage located within the Powder River Watershed. Five impoundment study sites are located within the LX Bar Creek Watershed; they include the Yates State, Termo, Bounty Hunter, Golden Eagle, and Waylon impoundments (See Figure 4-2).

Yates State Impoundment

The Yates State impoundment is located on a broad east-facing slope that originates to the west on steep buttes and extends into LX Bar Creek area to the east. The impoundment is located in the S ½ of the NE ¼ of the NW ¼ of Section 16, T56N, R75W. The impoundment reservoir has a capacity of 18.46 acre-feet and has been used to hold CBNG water for 6 years. The reservoir's water level is approximately 3,755 feet amsl. The Yates State impoundment is classified as an off-channel impoundment and is set above the alluvium of the LX Bar Creek. In 2006, two monitoring wells were drilled at the impoundment site; one up-gradient and one down-gradient of the impoundment reservoir. Both wells were drilled to define the shallow geology, to determine if there were impacts to groundwater as a result of infiltrating water from the impoundment and to provide background water quality data. The boring logs and well construction diagrams for all boreholes at the Yates impoundment are included in Appendix B. Table 4-5 provides a summary of borehole and monitoring well completion data for borings near the Yates State impoundment.

Area Geology - Yates State Impoundment

Wire-line logs from several CBNG wells were examined to map the subsurface geology in the vicinity of the impoundment. Two shallow coal seams were identified in these wells, the Upper Canyon coal and the Anderson coal. The Upper Canyon is most consistent across the area, showing a subtle NW-SE ridge with a dip into the hills to the west and a slight dip toward the creek to the east. The Upper Canyon coal was not intercepted in either of the monitoring wells; however, the Anderson coal was encountered in Yates State MW-2 well. A structure map contoured on the top of the Upper Canyon coal is shown in Figure 4-7. The Upper Canyon coal is seen to be almost flat over the area with a low relief ridge in the area of the impoundment. Near surface sediments appear to consist of variable thickness of regolith covering the bedrock surface on the broad slope. In the higher reaches of the area, little weathered material is present while at lower elevations regolith is present to a depth in excess of 40 ft.

Table 4-5: Summary of Borehole and Monitoring Well Completion Information at the Yates State Impoundment

Name	Gradient Position	Dist. From Impound.	Elev.	Depth to SWL	Elev. SWL	Depth to Bedrock	Lithology of the Water Zone	TD	Elev. at TD	Screen	Elev. of Screened Interval	Comments
Yates State MW-1	Up	150	3768	37.05	3731	3	Sandy Siltstone	57.5	3710	47-57	3710-3720	No coal beds encountered in this monitoring well.
Yates State MW-2	Down	100	3743	11.33	3732	22	Coal	31	3712	19-29	3714-3724	Anderson Coal (22-27') & (29-31+') bgs

Note: All measurements are in feet

Summary of Local Geology and Hydrogeology Conditions: Yates State Impoundment

The geology proximal to the Yates State impoundment appears to be discontinuous in nature. Soils and regolith consisting of clays and silty clays overlie bedrock, which appears at depths of 3 to 22 ft bgs in the site monitoring wells and depths of over 40 feet bgs in some of the adjacent CBNG wells. The predominant lithologies in the area are claystone, siltstone, and coal. A coal seam is present in Yates State MW-2 at a depth of 22 ft bgs; however, there was no coal encountered in the entire 57.5 ft of the Yates State MW-1 well.

Groundwater is present in sandy silts up-gradient of the impoundment at a depth of 46.5 ft bgs. A static water level reading for this groundwater measured 45.3 ft btc. Down-gradient of the impoundment, groundwater is found within the Anderson coal at 22 ft bgs and had a static water level of 10.7 ft btc (See calculations in Appendix D). Locally this coal appears to dip to the north. As the up-gradient and down-gradient wells are screened in different aquifers, the interpretation of possible infiltration from the impoundment will be problematic.

Bounty Hunter Impoundment

The Bounty Hunter impoundment is located on the south side of LX Bar Creek in the SW ¼ of the NE ¼ of Section 22 T56N R75W. The impoundment reservoir has a capacity of 13.41 acre feet and has been used to hold CBNG water for 6 years. The Bounty Hunter impoundment is considered to be an off-channel impoundment set on the edge of the alluvium of the LX Bar Creek and the south rim of the alluvial valley. The valley floor is quite broad in this area and rises steeply to buttes on the east and west sides of the valley. In 2006, two monitoring wells (Bounty Hunter MW-2 and MW-3) were drilled down gradient of the impoundment and four wells / boreholes (Bounty Hunter MW-1, DOE BH-1, BH-2, and BH-3) were drilled up-gradient of the impoundment (Figure 4-8, Appendix A). The monitoring wells were drilled to define the shallow geology, to determine if there were impacts to groundwater as a result of infiltrating water from the impoundment and to provide background water quality data. The up-gradient boreholes were drilled in support of an ongoing associated DOE groundwater flow study which includes geophysical logging of the borings. All boring logs and well construction information for the monitoring wells at the Bounty Hunter impoundment site are included in Appendix B. Table 4-6 provides a summary of borehole and monitoring well completion data for those boring / monitoring wells drilled in the area of the Bounty Hunter impoundment.

Area Geology - Bounty Hunter Impoundment

This geologic interpretation of the area near the Bounty Hunter impoundment was developed from analysis of the data collected from boreholes completed as part of the field effort in 2006 (Appendix B), wire-line logs from several nearby CBNG wells, and geophysical logs (Appendix B) that were collected after the completion of the borings drilled near the impoundment. The shallowest consistent coal is the Anderson coal at approximately 75 ft bgs. The structure map contoured on the Anderson Coal datum (Figure 4-8) shows slight dip on this horizon to the east at less than 100 feet per mile. The Anderson Coal was encountered in the Bounty Hunter MW-1 monitoring well and in three up-gradient soil borings (BH-1, BH-2, and BH-3). The Anderson coal may be present less than 40 ft below the base of the impoundment and very likely sub-crops beneath the alluvium of LX Bar Creek, northeast of the impoundment.

The location of Cross Section 4-4 (Appendix C) is show on the map in Figure 4-8 (Appendix A) as depicted by the line A-A'. Cross Section 4-4 shows the variable geology that exists in the subsurface near the Bounty Hunter impoundment. The shallow near surface area is comprised of bedded clays and sands from the upper area near MW-1 down the slope to the bottom area below the Bounty Hunter impoundment near MW-2 and MW-3 (Cross Section 4-4). In the upland areas the series of clays and sands is thicker with up to four sands seams of various thicknesses, while in the lowland area below the Bounty Hunter impoundment only one sand zone was identified in the borehole for MW-1 and is a coal seam that appears to have outcrop in the area of the impoundment. Below the lowest sand in the upland area is a coal seam that was interpreted to be the Anderson coal seam. The Anderson coal was not encountered in the wells below the impoundment; based on the apparent dip of the coal seam the two down-gradient wells would not have been deep enough to reach the Anderson coal.

Table 4-6: Summary of Borehole and Monitoring Well Completion Information at the Bounty Hunter Impoundment

Name	Gradient Position	Dist. From Impound.	Elev.	Depth to SWL	Elev. SWL	Depth to Bedrock	Lithology of the Water Zone	TD	Elev at TD	Screen	Elev. of Screened Interval	Comments
Bounty Hunter MW-1	Up	150	3827	36.7	3790		Coal	49	3778	28-48	3779-3799	Water zone interpreted to be in the Anderson Coal Seam at 38-43' bgs.
Bounty Hunter MW-2	Down	100	3792	18.2	3776		Sand	35	3757	24-34	3758-3768	Overburden soils mostly damp clays.
Bounty Hunter MW-3	Down	100	3793	18.65	3774		Clay with Sand and silt	35	3758	19-29	3764-3774	Soils similar to MW-2. Lost returns at 18' bgs, switched to HSA
DOE BH-1	Up	~325	3852	NA	NA		NA	119	3728	NA	NA	Anderson Coal Seam at 61-64' bgs; dry. Borehole not completed for monitoring.
DOE BH-2	Up	~325	3848	56.1	3792		Coal	74	3774	53-73	3775-3795	Anderson Coal Seam at 57-68' bgs; Damp to Wet.
DOE BH-3	Up		3843	NA	NA		Coal	88	3755	NA	NA	Anderson Coal Seam present, returns lost at 83' bgs. Borehole not completed as monitoring well

Note: Measurements are all in feet

Summary of Local Geology and Hydrogeology Conditions: Bounty Hunter Impoundment

The geology in the immediate vicinity of the Bounty Hunter impoundment is determined by the impingement of the LX Bar alluvium and the regional stratigraphy of mixed clastics and shallow Anderson coal. The impoundment is in the immediate vicinity of the stream valley of the LX Bar Creek and thin alluvium may be present beneath the impoundment. Alluvial deposits were found to be present in Bounty Hunter MW-2 and MW-3 located northeast of the reservoir. As the Anderson coal appears to sub-crop below the impoundment any water entering the Anderson coal aquifer via infiltration from the bottom of the impoundment could migrate toward LX Bar Creek and come in contact with the alluvium.

Termo Impoundment

The Termo Reservoir is located on the north side of LX Bar Creek in the SE ¼ of the NW ¼ of Section 15 T56N R75W. The impoundment has a capacity of 15.69 acre feet and has been used to hold CBNG water for 5 years. The water level in the impoundment is approximately 3840 ft amsl. The reservoir sits well above the alluvium of LX Bar Creek in a position near the base of a broad slope extending up to the buttes to northeast. The Termo impoundment is classified as an off-channel impoundment. In 2006, two monitoring wells were drilled down-gradient of the impoundment (Termo MW-2 and Termo MW-3) and one monitoring well (Termo MW-1) was drilled up-gradient of the impoundment (Figure 4-9, Appendix A). These wells were drilled to define the shallow geology, to determine if there were impacts to groundwater as a result of infiltrating water from the impoundment and to provide background water quality data. The boring logs and monitoring well completion diagrams are included in Appendix B. Table 4-7 is a summary of borehole and monitoring well completion data for the borings/monitoring wells drilled in the area of the Termo impoundment.

Table 4-7: Summary of Borehole and Monitoring Well Completion Information at the Termo Impoundment

Name	Gradient Position	Dist. From Impound.	Elev.	Depth to SWL	Elev. SWL	Depth to Bedrock	Lithology of the Water Zone	TD	Elev. at TD	Screen	Elev. of Screened Interval	Comments
Termo MW-1	Up	300	3884	107.7	3776	6	Sandy Siltstone and Coal	113	3771	93-113	3771-3791	The lithology of the near surface bedrock consists of claystones and sandy siltstones. Anderson Coal Seam (99-113+') bgs
Termo MW-2	Down	100	3845	69.98	3775		Coal	78	3767	58-78	3767-3787	Anderson Coal Seam (70-78+') bgs
Termo MW-3	Down	200	3837	63.6	3773	23	Sand and Coal	78	3759	58-78	3759-3779	Sand (63-68')bgs & Anderson Coal Seam estimated at (73-78') bgs. No returns from 68-78' bgs.

Note: Measurements are all in feet

Area Geology - Termo Impoundment

This geologic interpretation of the area near the Bounty Hunter impoundment was developed from analysis of the data collected from boreholes completed as part of the field effort in 2006 (Appendix B), wire-line logs from several nearby CBNG wells, and geophysical logs (Appendix B) that were collected after the completion of the borings drilled near the impoundment. The CBNG well logs showed two coal seams common to the area – the Anderson coal and the deeper Canyon coal. The shallowest Smith coal, which lies above the Anderson, was identified in only one CBNG well and likely outcrops in the area. The structure map of the Anderson coal in Figure 4-9 shows considerable dip to the southwest across the area, with measured dip in excess of 200 ft per mile. From the impoundment, the dip is in the direction of LX Bar Creek. The Anderson coal does not outcrop in the area of the impoundment. The shallowest coal is located at least 50 ft beneath the bottom of the impoundment.

The location of Cross Section 4-5 (Appendix C) is show on the map in Figure 4-9 (Appendix A) as depicted by the line A-A'. Cross Section 4-5 shows the shallow subsurface geology that exists near the Bounty Hunter impoundment. The shallow near surface area is comprised of clays and silts, with some sand present in the upland area near MW-1. At approximately 3,825 ft amsl there is a sand of variable thickness present across the region; the sand is thickest in the area of MW-2 (approximately 50 ft) and in the upland area near MW-1. In the area of MW-3 to the west, the sand is present only as a thin zone at the top of the interval replaced by nearly 45 ft of siltstones and claystones then present in a thin 5 foot zone at 3,775 ft amsl. Below this sand is a coal seam that was interpreted to be the Anderson coal seam. The Anderson coal was seen in cutting returns from the bottom of all three boreholes at this impoundment.

Summary of Local Geology and Hydrogeology Conditions: Termo Impoundment

The geology proximal to the Termo impoundment appears to be relatively consistent with overburden soils lying above bedrock that is present at depths of 6 to 23 ft bgs. Bedrock is composed primarily of claystones, siltstones, and sands. A coal seam is present in each monitoring well and appears to be correlative to the Anderson Coal seam identified in nearby CBNG wells (Cross Section 4-5 and Figure 4-10). The thickness of this coal seam in the area ranges between 4 feet and 12 feet. Mapping the top of the Anderson coal (Figure 4-10) shows the coal seam to be relatively horizontal. Groundwater appears in the coal as well as in a sand on the top of the coal. Analysis of measured static water levels indicates that groundwater within the coal and overlying sand flows towards the southeast with an estimated hydraulic gradient of 0.046 feet/feet (see calculations in Appendix D).

Waylon Impoundment

The Waylon impoundment is located on the north side of LX Bar Creek and west of the SA Road in the SE ¼ of the NW ¼ of Section 9 T56N R75W. The impoundment reservoir has a capacity of 19.6 acre-feet and has been used to hold CBNG water for 5 years. The approximate elevation of the water level in the impoundment is 3,750 ft amsl. The Waylon impoundment is considered to be an off-channel impoundment located on a broad slope above LX Bar Creek. In 2006, two monitoring wells (Waylon MW-2 and MW-3) were drilled down-gradient of the impoundment and one well (Waylon MW-1) was drilled up-gradient of the impoundment (Figure 4-10, Appendix A). These wells were drilled to define the shallow geology, to determine if there were impacts to groundwater as a result of infiltrating water from the impoundment and to provide background water quality data. The boring logs and monitoring well completion diagrams are included in Appendix B. Table 4-8 is a summary of borehole and monitoring well completion data for the borings / monitoring wells drilled in the area of the Waylon impoundment.

Area Geology - Waylon Impoundment

This geologic interpretation of the area near the Bounty Hunter impoundment was developed from analysis of the data collected from boreholes completed as part of the field effort in 2006 (Appendix B), wire-line logs from several nearby CBNG wells, and geophysical logs (Appendix B) that were collected after the completion of the borings drilled near the impoundment. Three coals were identified in the CBNG well logs – the Upper Canyon Coal, an unnamed coal seam, and the shallow Lower Cook Coal. The Upper Canyon is the most consistent coal over the area. As shown in Figure 4-10 this coal is seen to dip to the east across the area at the rate of approximately 100 feet per mile. This dip direction runs opposite to the slope of the land as it drops off the flat-topped butte to the east into the valley of the LX Bar Creek to the west. The three monitoring wells drilled at this site appear to have intercepted the Lower Cook coal seam at various depths; this shallow coal is also present in the Manigault No. 7-LW CBNG well to the east but is eroded at the location of Gabrielle CS wells to the northwest. Analysis of the Lower Cook coal in the vicinity of the reservoir shows the coal appears to dip slightly to the west, in the direction of the LX Bar Creek. The Lower Cook coal either outcrops in the LX Bar valley or is in contact with the alluvium of the stream.

THIS PAGE INTENTIONALLY LEFT BLANK

Table 4-8: Summary of Borehole and Monitoring Well Completion Information at the Waylon Impoundment

Name	Gradient Position	Dist. From Impound.	Elev.	Depth to SWL	Elev. SWL	Depth to Bedrock	Lithology of the Water Zone	TD	Elev. at TD	Screen	Elev. of Screened Interval	Comments
Waylon MW-1	Up	100	3762	36	3726		Clayey silt	50	3712	40-50	3712-3722	The lithology of the near surface bedrock consists of silty clays and clayey silts. Lower Cook Coal Seam (48-50') bgs
Waylon MW-2	Down	100	3748	48.3	3700		Silty Sand	64	3684	54-64	3684-3694	Near surface silty clays and clayey silts at near surface. Lower Cook Coal Seam (22-29') bgs.
Waylon MW-3	Down	100	3747	28	3719	18	Coal	39	3708	29-39	3708-3718	Lower Cook Coal Seam (29-28') bgs. With dry shale below the coal seam.

Note: Measurements are all in feet

The location of Cross Section 4-6 (Appendix C) is show on the map in Figure 4-10 (Appendix A) as depicted by the line A-A'. Cross Section 4-6 shows the shallow subsurface geology that exists near the Waylon impoundment. The shallow near surface area is comprised of clays and silts. At approximately 3,715 ft amsl there is a coal of variable thickness present across the region, this coal seam was interpreted to be the Lower Cook coal seam. Below the Lower Cook coal seam is a siltstone and claystone zone of up to 15 ft in thickness near MW-2. Below this siltstone and claystone zone appears to be a sand zone of unknown thickness as the borehole for MW-2 only partially penetrates this zone and neither of the other two boreholes penetrated this zone.

Summary of Local Geology and Hydrogeology Conditions: Waylon Impoundment

The geology proximal to the Waylon Reservoir appears to be relatively consistent with overburden clay soils above bedrock that is at approximately 18 ft bgs. Bedrock is composed of claystones and siltstones with lesser amounts of inter-bedded fine-grained sandstone. The Lower Cook coal seam is present throughout the impoundment area at depths of 22 to 48 ft bgs and has a thickness of 7 to 9 ft. Mapping the top of the coal indicates a local dip to the west. Groundwater is, however, not consistently associated with this coal seam. On the east side of the impoundment, groundwater occurs in a clayey silt a few feet above the coal (42 ft bgs, with a static water level 34.1 ft btc) and on the west side, groundwater is clearly within the coal strata as encountered in MW-3 (31 ft bgs, with a static water level 31.1 ft btc). Although MW-2 intersected the Lower Cook coal, it was dry and groundwater was not seen until almost 20 feet below this coal (59 ft bgs; static 46 ft btc) in a silty sand. Therefore, it appears there may be two groundwater zones proximal to the Waylon impoundment and they may also be geographically limited in their extent.

It appears the Lower Cook coal dips to the west in the vicinity of the impoundment. Since the groundwater elevations recorded in each well occur within approximately 25 ft of each other and the chemistry observed among the wells is similar, there is a slight possibility that the water tables may be in hydrologic connection. If this is the case, analysis of these data indicates that the aquifer exhibits a shallow dip of 11.17° to the northwest and a hydraulic gradient of 1,042 ft/mile (See calculations in Appendix E). However, based on present knowledge of the local lithology, the direction of the dip is more likely to be southeastward. It seems more likely that the groundwater in all three wells are not in direct communication and do not represent a single, continuous groundwater table. It is more probable that there are two or more isolated or perched water tables.

Golden Eagle Impoundment

The Golden Eagle impoundment is located in the drainage of a tributary on the north side of LX Bar Creek in the SE ¼ of the NE ¼ of Section 26 T56N R75W. The impoundment reservoir has a capacity of 29.82 acre-feet and has been used to hold CBNG produced water for 7 years. The Golden Eagle impoundment is an on-channel impoundment, built within the alluvial plain of a tributary of LX Bar Creek.

Area Geology - Golden Eagle Impoundment

This geologic interpretation of the area near the Golden Eagle impoundment was developed from analysis of the data collected from boreholes completed as part of the field effort in 2006 (Appendix B), wire-line logs from several nearby CBNG wells, and geophysical logs (Appendix B) that were collected after the completion of the borings drilled near the impoundment. The shallowest consistent coal is the Anderson coal found at approximately 350 ft bgs. Although the thinner Felix coal is seen on several CBNG well logs at approximately 60 feet bgs, the Anderson coal is likely the coal encountered in the Golden Eagle MW-1 well. A structure map contoured on the top of the Felix coal (Figure 4-11) shows dip to the northeast on this horizon in the vicinity of the reservoir. The Felix coal appears to outcrop in the LX Bar Creek to the south of the impoundment or is in contact with the alluvium of the creek. This coal may be present beneath the impoundment at a relatively shallow depth.

The location of Cross Section 4-7 (Appendix C) is show on the map in Figure 4-11 (Appendix A) as depicted by the line A-A'. Cross Section 4-7 shows the shallow subsurface geology that exists near the Waylon impoundment. The shallow near surface area is comprised of clays and silts. At approximately 3,855 ft amsl there is a coal of variable thickness present in the upland region near MW-1, this coal seam was interpreted to be the Anderson coal seam. Below the Anderson coal seam is a thin claystone zone of up to 5 ft in thickness, with another thin coal seam below this claystone. In the area to the south of the Golden Eagle impoundment near MW-2 and MW-3, there were signs of a sand zone at approximately 3,850 ft amsl that was not seen in either of the other two borings.

Table 4-9: Summary of Borehole and Monitoring Well Completion Information at the Golden Eagle Impoundment

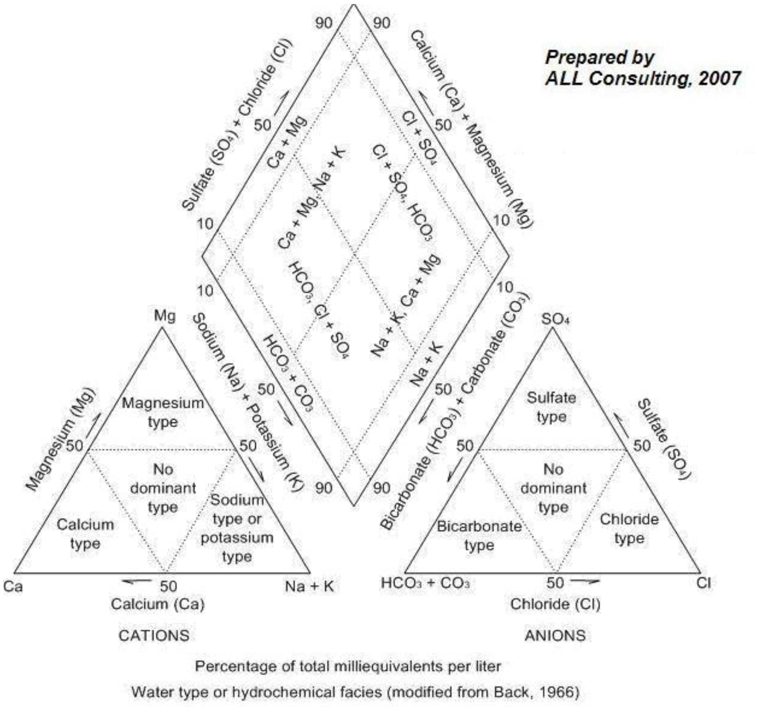
Name	Gradient Position	Dist. From Impound.	Elev.	Depth to SWL	Elev. SWL	Depth to Bedrock	Lithology of the Water Zone	TD	Elev. at TD	Screen	Elev. of Screened Interval	Comments
Golden Eagle MW-1	Up	220	3918	66.35	3852	7	Sandstone	101	3817	76.5-86.5	3831.5-3841.5	Hole caved back to 86.5 bgs prior to running casing for monitoring well.
Golden Eagle MW-2	Down	100	3870	18.2	3852		Sandy–Silty Clay	28	3848	18-28	3848-3858	Alluvial clay, silt and fine sand from surface to TD.
Golden Eagle MW-3	Down	200	3867	18.65	3848		Silt &Sand, Clay rich	25	3852	14.5-24.5	3852.5-3862.5	Alluvial clay and silt from surface to TD.
DOE LX-1	Up	1,130	4030	Dry				118	3912			Dry coal seams encountered at 25-29', 108-110', & at 117' bgs. Borehole not completed for monitoring.
DOE LX-2	Up	~1,130	4030	Dry				118	3912			Dry coal seams encountered at 26-30'and 111-113' bgs. Borehole not completed for monitoring.
DOE LX-3	Up	~1,130	4018	Dry				120	3898			Dry coal seams encountered at 28-30'and 113-115' bgs. Borehole not completed for monitoring.

Note: Measurements are all in feet

Summary of Local Geology and Hydrogeology Conditions: Golden Eagle Impoundment

The strata in the vicinity of the Golden Eagle impoundment appears to be essentially flat-lying with water present in the alluvium and in the deeper aquifer just below the tight sand encountered at approximately 80 feet below the surface in Golden Eagle MW-1. The water level in this deeper aquifer is below that in the alluvium aquifer, suggesting that this deeper aquifer is not connected with the alluvial system. The deeper aquifer is, however, at approximately the same elevation as the base of the impoundment reservoir and thus could sub-crop under the impoundment.

Figure 4-1: Generalized Piper Plot for Groundwater Samples



Prepared by ALL Consulting, 2007

Percentage of total milliequivalents per liter

Water type or hydrochemical facies (modified from Back, 1966)

Water from this reservoir probably flows into the alluvial system of the LX Bar drainage. The bottom of the drainage is approximately the same level as the static water levels found in Golden Eagle MW-2 and MW-3 which are located on either side of the drainage. There is lush vegetation in the bottom of the drainage that is sustained by groundwater in the alluvium and / or possible infiltrate from the impoundment.

Water from Golden Eagle MW-1 is from an unknown coal seam and underlying bedrock while water from MW-2 and MW-3 are from shallow alluvial aquifers; therefore, the aquifers are not correlative. The alluvial aquifer likely occurs throughout the draw beneath the impoundment and MW-2 and MW-3 can be used to monitor water quality within the alluvium below the impoundment, but not necessarily above it. The MW-1 bedrock aquifer may or may not be connected with the alluvial system in the area of the impoundment, but water quality at this point does not under these conditions necessarily reflect the background water quality of the alluvial aquifer up-gradient of the impoundment.

ANALYSIS OF OBSERVED GROUNDWATER IMPACTS

Analysis of the groundwater chemistry of aquifers and of CBNG produced waters can be performed by evaluating posted analytical plots of a variety of chemical constituents present in the water. The analysis of TDS and SAR are commonly utilized to evaluate CBNG waters as a measure of suitability for agricultural uses including both livestock watering and for land application/irrigation. Other analysis performed to determine compliance with state required monitoring may focus on common and trace metals present in the waters for comparison to guidance levels. In terms of water origin analysis and evaluating water-bedrock interactions, analysis is focused on the major dissolved ionic constituents including the cations of sodium, potassium, calcium, magnesium, and the anions of bicarbonate, chloride, sulfate, and carbonate.

Piper diagrams can be used to analyze the composition of most natural waters in the terms of the major cation and anion species (Hem, 1985). The above figure shows the basic layout of the Piper diagram separated into its respective water quality zones. For the groundwater analysis performed in this research, the geochemical analysis focused on evaluating water chemistry data in terms of the major cation and anion data as depicted on a Piper diagrams as well as the evaluation of TDS and SAR data for the samples.

Piper diagrams have long been used to study water chemistry. The two triangles at the bottom of the diagrams correspond to cations and anions, with each vertex representing 100 percent of a particular ion or groups of ions. Water quality is established by the diamond shaped area in which the two points plotted in the triangles are projected into the diamond and are plotted as a single point. The Piper diagram shows how water quality characteristics, cations and anions are separated into the components of the Piper diagram. Interpretations of water quality can be made from the single point projected into the diamond. The Piper diagrams allow for a visual comparison and thus an analysis of the quality of two or more groundwater samples. The Piper plot does not, however, provide analysis for changes in concentrations of the major ions; other analytical methods are used to assess changes in overall ionic concentration including TDS analysis and ion plots.

ANALYSIS OF GEOCHEMICAL DATA FROM IMPOUNDMENTS LOCATED OVER ALLUVIAL AQUIFERS ALONG THE POWDER RIVER OF WYOMING

Earlier portions of this document discuss the anticipated impacts associated with the infiltration of CBNG impoundment water; one of the major conditions that was identified as influencing the changes in chemistry as the water infiltrates was the local geology. In an effort to in part account for this condition in this research the data analysis has been separated by aquifer type. This section presents a summary of the results of geochemical monitoring data gathered at infiltration impoundments which were sited and completed at locations over alluvial aquifers; a more detailed discussion of this analysis is presented in Appendix E. The impoundment sites include the East Arvada sites (Jeff 3, Jeff 5, Jeff 6, and Jeff 7 impoundments) and the West Arvada sites (Phil's Pond, Candida 2, N. Cottonwood 8, Santiago 3, and Tietjen impoundments).

East Arvada Sites

The four impoundment sites studied associated with the alluvial aquifers were the Jeff 3, Jeff 5, Jeff 6, and Jeff 7. The locations of these sites can be seen on Figure 4-3 (Appendix A). Each of these impoundment sites were constructed over alluvial aquifers along the Powder River, with all the wells completed in the same alluvial aquifer system. The groundwater sampling conducted for these impoundments included at least one background sample collected at each monitoring well prior to CBNG being discharged into the impoundment.

The alluvial groundwater under the Jeff 3 impoundment site showed signs of the groundwater being altered by CBNG produced water infiltrating through the bottom of the impoundment. Simple mixing analysis that was conducted based on the background water and the CBNG produced water quality shows evidence to indicate that the alteration to groundwater that is seen in the alluvial aquifer is primarily simple mixing. This indicates that soluble salts are not present in high concentrations in the underlying soils, which is expected given that alluvial materials should be flushed of soluble salts on a regular basis by flooding. The groundwater samples at the Jeff 3 impoundment showed that initial alteration of groundwater toward greater than 75% CBNG produced water was seen within the first year of sampling. Analysis of the groundwater sampling results showed mixing in the Jeff 3 alluvial groundwater was altered to greater than 75% CBNG produced water quality. Also, the groundwater sample data for Jeff 3 (as shown in Appendix E) demonstrates that the groundwater in the alluvial aquifer while showing evidence of mixing with infiltrating produced water also showed signs of recovering toward the background water quality.

The alluvial groundwater under the Jeff 5 impoundment site showed signs of the groundwater being altered by CBNG produced water infiltrating through the bottom of the impoundment. Simple mixing analysis that was conducted based on the background water and the CBNG produced water quality shows evidence to indicate that the alteration to groundwater that is seen in the alluvial aquifer is primarily simple mixing. The groundwater samples at the Jeff 5 impoundment showed that initial alteration of groundwater toward greater than 25% CBNG produced water was seen within the first year of sampling. Analysis of the groundwater sampling results showed mixing in the Jeff 5 alluvial groundwater was altered to greater than 50% CBNG produced water quality. In addition, the groundwater sample data for Jeff 5 (as shown in Appendix E) demonstrates that the groundwater in the alluvial aquifer while showing evidence of mixing with infiltrating produced water also showed signs of recovering toward the background water quality.

Down-hole Geophysical Logging, LX Bar Creek Watershed, Wyoming

The alluvial groundwater under the Jeff 6 impoundment site showed signs of the groundwater being altered by CBNG produced water infiltrating through the bottom of the impoundment. Simple mixing analysis that was conducted based on the background water and the CBNG produced water quality shows evidence to indicate that the alteration to groundwater that is seen in the alluvial aquifer is primarily simple mixing. The groundwater samples at the Jeff 6 impoundment showed that initial alteration of groundwater toward 75% CBNG produced water was seen within the first two years of sampling. Analysis of the groundwater sampling results also showed mixing in the Jeff 6 alluvial groundwater was altered to greater than 75% CBNG produced water quality. The groundwater sample data for Jeff 6 (as shown in Appendix E) demonstrates that the groundwater in the alluvial aquifer while showing evidence of mixing with infiltrating produced water also starts to show signs of recovering toward the background water quality during the final year of sampling.

The alluvial groundwater under the Jeff 7 impoundment site showed signs of the groundwater being altered by CBNG produced water infiltrating through the bottom of the impoundment. Simple mixing analysis that was conducted based on the background water and the CBNG produced water quality shows evidence to indicate that the alteration to groundwater that is seen in the alluvial aquifer is primarily simple mixing. The groundwater samples at the Jeff 6 impoundment showed that initial alteration of groundwater toward greater than 75% CBNG produced water was seen at four years of sampling. Analysis of the groundwater sampling results also showed mixing in the Jeff 6 alluvial groundwater was altered to greater than 50% CBNG produced water quality. The groundwater sample data for Jeff 7 (as shown in Appendix E) demonstrates that the groundwater in the alluvial aquifer showed evidence of mixing with infiltrating produced water during the final year of sampling,; there was no indication of the groundwater recovering toward background water quality.

In summary, the four impoundments located in the East Arvada area all showed signs of mixing between background water quality and CBNG produced water quality. The timing and degree of mixing varied between the different impoundments, while one impoundment shows signs of alteration as early as the first sample after the background sample. One of the other impoundments did not show signs of alteration to the alluvial groundwater until the fourth year after discharge had been initiated at the impoundment. The degree of alteration seen at the impoundments varied from greater than 75% at two of the impoundments to slightly more than 50% at the other two impoundments.

West Arvada Sites

The five impoundment sites studied associated with the alluvial aquifers were the Phil's Pond, Candida 2, Cottonwood 8, Santiago 3, and Tietjen. The locations of these sites can be seen on Figure 4-3 (Appendix A). Each of these impoundment sites were constructed over alluvial aquifers along the Powder River, with all the wells completed in the same alluvial aquifer system. The groundwater sampling conducted for these impoundments included at least one background sample collected at each monitoring well prior to CBNG being discharged into the impoundment.

The alluvial groundwater under the Phil's Pond impoundment site showed signs of the groundwater being altered by CBNG produced water infiltrating through the bottom of the impoundment. Simple mixing analysis that was conducted based on the background water and the CBNG produced water quality shows evidence to indicate that the alteration to groundwater that is seen in the alluvial aquifer is primarily simple mixing. The groundwater samples at the Phil's Pond impoundment showed that initial alteration of groundwater toward greater than 25% CBNG produced water was seen after the third year of sampling. Analysis of the groundwater sampling results also showed mixing in the Phil's Pond alluvial groundwater was altered to greater than 25% CBNG produced water quality. The groundwater sample data for Phil's Pond (as shown in Appendix E) demonstrates that the groundwater in the alluvial aquifer while showing evidence of mixing with infiltrating produced water; there was no indication of the groundwater recovering toward background water quality.

The alluvial groundwater under the Candida 2 impoundment site showed signs of the groundwater being altered by CBNG produced water infiltrating through the bottom of the impoundment. Simple mixing analysis that was conducted based on the background water and the CBNG produced water quality shows evidence to indicate that the alteration to groundwater that is seen in the alluvial aquifer is primarily simple mixing. The groundwater samples at the Candida 2 impoundment showed that initial alteration of groundwater toward greater than 50% CBNG produced water was seen within the first year of sampling. Analysis of the groundwater sampling results also showed mixing in the Candida 2 alluvial groundwater was altered to greater than 75% CBNG produced water quality. The groundwater sample data for Candida 2 (as shown in Appendix E) demonstrates that the groundwater in the alluvial aquifer shows evidence of mixing with infiltrating produced water; however there was no indication of the groundwater recovering toward background water quality.

The alluvial groundwater under the Santiago 3 impoundment site showed signs of the groundwater being altered by CBNG produced water infiltrating through the bottom of the impoundment. Simple mixing analysis that was conducted based on the background water and the CBNG produced water quality shows evidence to indicate that the alteration to groundwater that is seen in the alluvial aquifer is primarily simple mixing. The groundwater samples at the Santiago 3 impoundment showed that initial alteration of groundwater toward greater than 25% CBNG produced water was seen within the first year of sampling. Analysis of the groundwater sampling results also showed mixing in the Santiago 3 alluvial groundwater was altered to greater than 75% CBNG produced water quality. The groundwater sample data for Santiago 3 (as shown in Appendix E) demonstrates that the groundwater in the alluvial aquifer while showing evidence of mixing with infiltrating produced water with evidence of the groundwater recovering toward background water quality.

The alluvial groundwater samples collected at the N. Cottonwood 8 and Tietjen impoundment sites showed no signs of the groundwater being altered by CBNG produced water infiltrating through the bottom of the impoundment. While the groundwater samples did show some variation in sample quality, there was no indication of the groundwater being altered by mixing.

In summary, the three of the five impoundments located in the West Arvada area showed signs of mixing between background water quality and CBNG produced water quality. The timing and degree of mixing varied between the different impoundments, one impoundment show signs of alteration as early as the first sample after the background sample. One of the other impoundment did not show signs of alteration to the alluvial groundwater until late in the third year after discharge had been initiated at the impoundment. The degree of alteration seen at the impoundments varied from greater than 75% at two of the impoundments, to slightly more than 25% at the one of the impoundments, to no observed alteration at two of the impoundments.

ANALYSIS OF GEOCHEMISTRY DATA FROM IMPOUNDMENTS WITHIN THE TONGUE RIVER AND POWDER RIVER WATERSHEDS OF WYOMING

During the discussion of anticipated impacts associated with the infiltration of CBNG impoundment water one of the major conditions that were identified as influencing the changes in chemistry as the water infiltrates was the local geology. This section presents the results of monitoring chemical data for impoundments which were completed over non-alluvial aquifers. The lithologic composition of the materials present below these impoundments is described in the geology discussion in Section 4.3 of this document.

Earlier portions of this document discuss the anticipated impacts associated with the infiltration of CBNG impoundment water. One of the major conditions that was identified as influencing the changes in chemistry as the water infiltrates was the local geology. In an effort to in part account for this condition in this research the data analysis has been separated by aquifer type. This section presents a summary of the results of geochemical monitoring data gathered at infiltration impoundments which were sited and completed at locations over non-alluvial aquifers; a more detailed discussion of this analysis is presented in Appendix E. The impoundment sites include the Prairie Dog Creek sites (Sandy, Lori, and Joe Draw Jr. impoundments) and the LX Bar Creek sites (Yates State, Bounty Hunter, Termo, Waylon, and Golden Eagle impoundments).

Prairie Dog Creek Sites

The three impoundment sites from the Prairie Dog Creek site studied in association with the non-alluvial aquifers were the Sandy, Lori, and Joe Draw Jr. impoundments. The locations of these sites can be seen on Figure 4-1 (Appendix A). Each of these impoundment sites were constructed over bedrock aquifers along the Prairie Dog Creek watershed, with all the wells completed in the first groundwater system encountered during drilling. The groundwater sampling conducted for these impoundments included one sample collected at each monitoring well. The groundwater samples were all collected after groundwater had been discharged into the impoundments for at least two years.

The first groundwater aquifer identified under the Lori impoundment site is located in a coal seam aquifer. Analysis of the background water quality sample in the shallow coal seam near the Lori impoundment showed water quality with significant difference from the CBNG produced water quality in the area. The groundwater under the Lori impoundment showed evidence of a simple mixing between background water quality and CBNG produced water quality. The groundwater down-gradient of the Lori impoundment shows evidence of alteration toward CBNG produced water away from background quality to greater than 75% CBNG produced water at one location.

The first groundwater aquifer identified under the Sandy impoundment site is located in a coal seam aquifer, and a shallow perched aquifer in the surface drainage present below the impoundment dam. Analysis of the background water quality sample in the shallow coal seam near the Sandy impoundment showed water quality with significant difference from the CBNG produced water quality in the area. The groundwater under the Sandy impoundment showed no evidence of mixing between background water quality and CBNG produced water quality. The groundwater down-gradient of the Sandy impoundment shows no evidence of alteration toward CBNG produced water; the shallow perched aquifer also showed no evidence of alteration toward CBNG produced water.

The first groundwater aquifer identified under the Joe Draw Jr. impoundment site is located in a siltstone/coal seam aquifer. Analysis of the background water quality sample in the coal seam below the Joe Draw Jr. impoundment showed water quality very similar to the CBNG produced water quality in the area. The groundwater under the Joe Draw Jr. impoundment showed no evidence of mixing between background water quality and CBNG produced water quality; however, because of the similarities of the two waters it is very difficult to distinguish if there is mixing.

LX Bar Creek Sites

The five impoundment sites studied from the LX Bar Creek associated with the non-alluvial aquifers were the Yates State, Bounty Hunter, Termo, Waylon, and Golden Eagle impoundments. The locations of these sites can be seen on Figure 4-2 (Appendix A). Each of these impoundment sites were constructed over bedrock aquifers along the LX Bar Creek watershed, with all the wells completed in the first groundwater system encountered during drilling. The groundwater sampling conducted for these impoundments included one sample collected at each monitoring well. The groundwater samples were all collected after groundwater had been discharged into the impoundments for at least two years.

The first groundwater aquifer identified under the Yates State impoundment site is located in a coal seam aquifer. Analysis of the background water quality sample in the shallow coal seam near the Yates State impoundment showed water quality with significant difference from the CBNG produced water quality in the area. The groundwater under the Yates State impoundment showed evidence of a simple mixing between background water quality and CBNG produced water quality. The groundwater down-gradient of the Yates State impoundment shows evidence of alteration toward CBNG produced water away from background quality to greater than 25% CBNG produced water at one location.

The first groundwater aquifer identified under the Bounty Hunter impoundment site is located in a sand/coal seam aquifer. Analysis of the background water quality sample in the shallow coal seam near the Bounty Hunter impoundment showed water quality with significant difference from the CBNG produced water quality in the area. The groundwater under the Bounty Hunter impoundment showed evidence of a simple mixing between background water quality and CBNG produced water quality. The groundwater down-gradient of the Bounty Hunter impoundment shows evidence of alteration toward CBNG produced water away from background quality to 50% CBNG produced water at one location; a second location showed greater than 75% CBNG produced water. This second location shows alteration that included additional changes away from simple mixing, which may indicate a line of more soluble salt concentrations within the soils (see Figure 5-101, in Appendix F).

The first groundwater aquifer identified under the Termo impoundment site is located in a coal seam aquifer. Analysis of the background water quality sample in the shallow coal seam near the Termo impoundment showed water quality with significant difference from the CBNG produced water quality in the area. The groundwater under the Termo impoundment showed evidence of a simple mixing between background water quality and CBNG produced water quality. The groundwater down-gradient of the Bounty Hunter impoundment shows evidence of alteration toward CBNG produced water away from background quality to 25% CBNG produced water at one location; a second location showed alteration away from background quality opposite of the CBNG produced water quality. The first location shows alteration that included additional changes away from the simple mixing which may indicate a line of more soluble salt concentrations within the soils (see Figure 5-101, in Appendix F).

The first groundwater aquifer identified under the Waylon impoundment site is located in a coal seam aquifer and a separate sand aquifer. Analysis of the background water quality sample in the shallow coal seam near the Waylon impoundment showed water quality with significant difference from the CBNG produced water quality in the area. The coal seam groundwater under the Waylon impoundment showed evidence of a simple mixing between background water quality and CBNG produced water quality. A second groundwater encountered during the drilling below the impoundment showed water quality that was different from background quality, but not along the mixing line of CBNG produced water quality (see Figure 5-105, Appendix F). The groundwater down-gradient of the Waylon impoundment shows evidence of alteration toward CBNG produced water away from background quality to greater than 25% CBNG produced water at one location. The coal seam aquifer shows alteration that included additional changes away from the simple mixing (see Figure 5-105).

The first groundwater aquifer identified under the Golden Eagle impoundment site is located in a coal seam aquifer and a separate silty-sand aquifer. Analysis of the background water quality sample in the shallow coal seam near the Golden Eagle impoundment showed water quality with significant difference from the CBNG produced water quality in the area. The coal seam groundwater under the Waylon impoundment showed no evidence of simple mixing between background water quality and CBNG produced water quality. A second groundwater encountered during the drilling below the impoundment dam showed water quality that was different from background quality, but not along the mixing line of CBNG produced water quality (see Figure 5-107, Appendix F). The groundwater down-gradient of the Waylon impoundment shows no evidence of alteration toward CBNG produced water (see Figure 5-107).

CONCLUSIONS

The research effort was successful in providing a more detailed understanding of CBNG produced water management practices in the PRB, with a focus on impoundments and infiltration of produced water. The following bullets highlight the lessons learned and conclusions from the research that was conducted by ALL Consulting and its cooperators.

1. The research effort was successful largely through the cooperation between a variety of state and federal agencies, industry, and consultants. The Wyoming Department of Environmental Quality and the lead researchers at ALL Consulting were able to accomplish a highly successful collaborative effort. Cooperation not only reduced costs for both entities but also simplified the regulatory burden on the project field work as WDEQ contributed field personnel during the field investigation portion of the research. By having WDEQ personnel in the field, ALL Consulting was able to utilize WDEQ's contacts in obtaining access to impoundments and cooperation from landowners and CBNG operators. WDEQ benefitted from having ALL Consulting screen the

drilling subcontractor to perform the borehole drilling and monitoring well installation, which allowed WDEQ to use the same subcontractor. WDEQ also benefited from having ALL Consulting develop much of the planning materials including the QAPP and SOP for the project. ALL Consulting benefited from having the WDEQ state laboratory analyze groundwater samples collected for this project to ensure consistency and compliance with the QAPP.

In addition to the cooperation between ALL Consulting and WDEQ, the USGS supplied field personnel and instrumentation to perform geophysical logging of geotechnical borings and monitoring wells installed during this research. Collaboration enabled the collection of large amounts of data which could be shared at a reduced cost to each individual cooperator. The DOE was also a cooperator in a variety of ways, in addition to funding the project; the DOE was instrumental in identifying the locations of four of the subsurface investigation sites in this study based on previous research the DOE has conducted in the PRB. The DOE benefited by having ALL Consulting and WDEQ collect data that was shared with the DOE to further leverage and enhance their research and investigations related to the management of CBNG produced water in the PRB.

Other cooperators include the MBOGC who in addition to assisting in providing funding for this project also contributed review and input in the development of the work plan and the investigation strategy for field work. MBOGC has acted as one of the primary contributors of information and input for this project including reviewing and acting as co-writers on the following complete aspects of this project; the re-injection paper (2004), the water statistics paper (2005), and the siting, design, and construction paper (2007) completed by ALL Consulting. The personnel of MBOGC have provided direction and input that has helped to guide this research project throughout the entire study and have provided reviews of all the documents that have been developed during the course of this research effort.

2. As part of the field investigation portion of this project, ALL Consulting and WDEQ worked together to develop a comprehensive QAPP and SOP for the collection of field data. ALL Consulting and WDEQ determined that it was important to develop the QAPP and SOP documents to ensure that the groundwater, borehole, and soil data collected during this project was repeatable and of the highest-quality. The decision to go through the process of developing these quality control documents was reached after a review of comments that were issued regarding prior water quality research conducted by industry, state, and federal agencies.

3. Over the course of this research project complications associated with the scheduling and performing field work in the Powder River Basin became readily apparent to the research team. Issues associated with performing the field work included weather conditions, and addressing land owners concerns to ensure there was no unnecessary damage to the land surface resulting from the investigation activities. The weather conditions during the spring and fall resulted in a land surface that is very slick, muddy and can potentially be extensively rutted or scarred by vehicles and equipment; therefore, field work had to be conducted either in the summer after the landscape was able to dry out or in the winter after the frost. Landowners have had to accept the disturbances associated with CBNG operators coming onto the surface and installing the necessary equipment to produce the CBNG, and are therefore hesitant to allow further intrusion which could potentially cause additional disturbance of their land. Therefore, it was important for this research to be conducted under the guidance of landowners to ensure that only minimal land disturbance occurred as a result of drilling or other investigatory activities.

   Outside of landowner and weather concerns, the scheduling of field work activities had to account for the availability of drilling subcontractors and to some extent the work schedules of the CBNG operators. The rapid expansion of CBNG development in the PRB has resulted in the time drilling subcontractors have been available as being at a premium. Drilling contractors who are capable of drilling CBNG production wells are not readily available during the drilling season, and those contractors who are capable of drilling monitoring wells are being used by both the CBNG and coal mining industries. Because of this high demand for these subcontractor resources, any deviation or alteration in schedule can cause additional delays while the subcontractor meets other commitments. Understanding that under some circumstances these delays cannot be avoided and trying to incorporate some delay time into a project conducted in this area aids in managing the changes and delays which do occur.

4. The subsurface investigation conducted as part of this research project provided additional support to document the highly variable geology that is present in the shallow subsurface of the PRB (see cross-sections in Appendix C). The quaternary alluvium, Wasatch and Fort Union Formations present in the shallow subsurface of the PRB are a varied mix of inter-bedded silts, clays, sands, and coals which are heterogeneous and anisotropic. Because of the heterogeneity and anisotropy of these geologic materials, groundwater flow does not always follow the topographic landscape which makes the fate of infiltrating water more complicated for state regulatory agencies and CBNG operators to understand and predict.

5. The complex geology that is present across much of the PRB may also require a more extensive investigative effort to fully understand the complex hydrogeologic systems present near impoundments. It may be possible in some areas of the PRB to install the minimum three monitoring wells needed to understand a single groundwater aquifer and determine the direction of groundwater flow. However, the geologic conditions identified during this investigation illustrate that investigations at many impoundment sites in the PRB may require more than three monitoring well to sufficiently understand the groundwater system under an impoundment.

   Other subsurface investigative techniques (such as 3D geophysical surveys) were not conducted as part of this research, however these techniques may help in defining the subsurface geology and in minimizing the number of monitoring wells or boreholes that need to be drilled in order to develop an understanding of the conditions present under an impoundment. Without an adequate subsurface investigation it is difficult for CBNG operators or regulators to accurately assess the fate of CBNG produced water that is allowed to infiltrate through the bottom of an impoundment.
6. The analysis of groundwater data from nine impoundments constructed over alluvium showed chemical changes at seven of those impoundments which were attributed to the mixing of CBNG water with existing groundwater as reflected by decreases in TDS. As was detailed through the review of the Piper diagrams in Appendix E, the data from the seven alluvial impoundments which showed evidence of mixing was indicative of a simple mixing process between two fluids with little to no outside influence that could be attributed to leaching or flushing of constituents present within the geologic media. One of the nine impoundments constructed over alluvium showed an approximate 100% increase in TDS, and data from the other impoundment showed no discernable change in shallow groundwater quality. At none of these impoundments were changes in TDS observed at a level comparable to that which was reported from the investigation of the Skewed reservoir as conducted by the BLM and USGS in 2004. The data observed from the shallow alluvial aquifers in this research showed decreases in TDS concentrations which would indicate an improved groundwater quality. At several of the sites, water quality as reflected by TDS concentration

7. Of the seven impoundments completed over alluvium which showed chemical changes as a result of mixing, three demonstrated signs of recovery towards pre-infiltration groundwater quality, while four impoundments appeared to show continuing additional chemical changes reflective of continued mixing with CBNG water which may be indicative of a longer flow path for the infiltrating water or a longer duration of discharge into the impoundment.

8. The analysis of the groundwater data from impoundments constructed on non-alluvium bedrock showed different chemical compositions which were attributed to mixing of CBNG water with existing groundwater at three of the eight impoundments studied. The groundwater data also indicated that four of the eight bedrock impoundments documented a chemical change which did not appear to be attributable to mixing of CBNG with existing groundwater. The chemical changes observed at these four impoundments may be reflective of additional alterations occurring to the groundwater as it moves through the subsurface, or may simply be representative of different groundwater zones in the subsurface. Only one impoundment completed over the bedrock aquifers showed no post-infiltration change in groundwater chemistry; the first groundwater zone encountered at this site was a coal seam.

9. During the course of this study several data gaps were identified related to infiltration impoundments in the PRB. First, there is very little data being collected to document the volume of water that is being discharged into CBNG impoundments; it is therefore impossible to determine an accurate water budget for those impoundments. The lack of data on discharges into impoundments also prevents the determination of the volume of water that is infiltrating into the subsurface. Lack of water input data also limits the ability to assess the potential for alluvial groundwaters to be discharged to surface waters as a result of mounding of the infiltrating water. At most impoundments volumetric data of water discharge to impoundments could be collected by operators with little effort. Regulators should consider the addition of a volumetric flow requirement to monitoring data, as volumetric input data would allow regulators to more accurately assess the potential impact of infiltrating water on groundwater systems.

10. The current WDEQ impoundment monitoring programs facilitates the WDEQ's assessment of the current water quality standards however; the program does not currently require operators to report the major cations (Ca, Mg, Na, K) and anions (SO_4, Cl, HCO_3, CO_3) present within the water. The major ions present in most groundwaters are used to study systematic changes to the composition and quality of groundwater systems. Because most groundwaters in the PRB have different chemical compositions than CBNG produced water, analysis of the major ions would facilitate assessment of the extent of chemical alteration to groundwater from infiltration. By requiring this analysis, assessment of the ions would allow the study of systemic changes to groundwater chemistry near impoundments and in the future may explain the recovery of shallow groundwater systems.

11. A review of the results and data present in this report does not suggest that impoundments should cease to be used as a means to manage CBNG produced water in the PRB. The groundwater monitoring data presented here does not provide evidence that the alteration by infiltrating water observed by other researchers (BLM, USGS, and MBMG) at impoundment sites are being seen at all such impoundments. In some instances such as the alluvial aquifers of the Powder River where the water quality in the aquifers is already poor, the infiltration of CBNG produced water from an impoundment actually can result in an improved mixed water quality in terms of TDS. The monitoring of groundwater as is currently required by WDEQ with the addition of suggested major ion parameters and discharge volume data should preclude irreversible alterations to groundwater quality in the shallow subsurface by infiltration impoundments.
12. Finally, while the results presented here show that impacts to the shallow aquifer (“first water”) systems appear to be short term in duration with some alteration in quality, additional research is necessary to assess the potential for infiltrating groundwater to extend into lower groundwater systems. This study focused solely on analysis of the potential for impacts that occur to first groundwater encountered.
13. Additional research considerations regarding impoundments in the PRB would include evaluation of methods to quickly assess groundwater under an impoundment by evaluating surface screening methods. As an example the potential exists for surface geophysics to be utilized as a screening tool which may aid in identifying groundwater that has been altered by infiltrating water. Surface geophysics in combination with an active monitoring well drilling program could facilitate a study that follows the alteration of the water system as it proceeds through the infiltration process to trace a plume.

REFERENCES

ALL Consulting and MBOGC. 2006. Siting, Design, Construction and Reclamation Guidebook for Coalbed Natural Gas Impoundments, prepared for the US DOE NETL, May 2006.

ALL Consulting. 2005. Surface Water and Groundwater Resources of the Powder River Basin and Implications for CBNG Development, prepared for the US DOE NETL.

ALL Consulting. 2004. Coal Bed Natural Gas Handbook, prepared for the US DOE NETL.

ALL Consulting. 2003. Handbook on Coal Bed Methane Produced Water: Management and Beneficial Use Alternatives, prepared for the US DOE, July 2003.

ALL Consulting. 2001. Water Resources Technical Report, Montana Statewide Oil and Gas Environmental Impact Statement and Amendment of the Powder River and Billings Resource Management Plans prepared for the United States Department of the Interior, Bureau of Land Management, Miles City Field Office.

Advanced Resources International, Inc (ARI). 2002. Powder River Basin Coalbed Methane Development and Produced Water Management Study prepared for U.S. DOE NETL, DOE/NETL-2003/1184

Ayers, W.B. 2002. Coalbed Methane Systems, Resources, and Production, AAPGB, Vol. 86, No. 11, 1853-1890.

Barak, Phillip, and Nater, Ed. 2003. Virtual Museum of Minerals and Molecules. http://www.soils.umn.edu/virtual_museum/index.html

Bartos, Timothy T. and Ogle, Kathy Muller. 2002, Water Quality and Environmental Isotopic Analyses of Ground-Water Samples Collected from the Wasatch and Fort Union Formations n Areas of Coalbed Methane Development - Implications to recharge and Ground-Water Flow, Eastern Powder River Basin, Wyoming. U.S. Geological Survey Water-Resources Investigations Report 02-4045.

Boutwell, G.P. and T.A. Lawrence. 1988. Electromagnetic Data Interpretation Using Multivariate Least-Square Regression. In: Proc. of the Focus Conf. on Eastern Regional Ground Water Issues (Stanford, CT), National Water Well Association, Dublin, OH, pp. 3-20.

CBM Associates, Inc. 2003. Effects of Impounded Coal Bed Methane Water Infiltration on Alluvial Groundwater and Surface Water Quality of the Powder River near Arvada, Wyoming. April 2001 through December 2002, prepared for Pennaco Energy, Inc. Gillette, Wyoming, submitted to WDEQ in June 2003.

CBM Associates, Inc. 2005. Annual Data Report, Alluvial Groundwater and Surface Water of the Powder River near Arvada, Wyoming. January 2003 through December 2004. Prepared for Pennaco Energy, Inc. Gillette, Wyoming, submitted to WDEQ in June 2005.

Cox, D. 2001. Coalbed Methane in the Rockies: Christmas Past, Present and Future, SPE Symposium on CBM in the Western US, Denver, CO, Jan. 2001.

DeLapp, Bill. 2005. Phone correspondence with Jake Crissup (ALL Consulting). March 16, 2005.

Domenico, Patrick A., and Franklin W. Schwartz. 1998. Physical and Chemical Hydrogeology, Second Edition, John Wiley & Sons, New York.

Ellis, M.S., Flores, R.M., Ochs, A.M., Stricker, G.D., Gunther, G.L., Rossi, G.S., Bader, L.R., Schuenemeyer, J.H., and Power, H.G. 1999. Gillette coalfield, Powder River Basin: Geology, coal quality, and coal resources: U.S. Geological Survey Professional Paper 1625-A, Chapter PG, pg. 1-79

Fetter, C.W. 1994. Applied Hydrogeology, Third Edition, Macmillan College Publishing Company, New York.

Fidelity Exploration and Production Company. 2004. CX Field 2003 Annual Groundwater Monitoring Report to the Montana Board of Oil and Gas Conservation Commission, March, 2004.

Flores, R.M., Weaver, J.N., Bossiroy, D., and Thorez, J. 1990. Genesis of clay mineral assemblages and micropaleoclimatic implications in the Tertiary Powder River Basin, Wyoming.

Freeze, R. Allan, and John A. Cherry. 1979. Groundwater, Prentice Hall, Englewood Cliffs, NJ.

Heffern, E.L. and Coates, D.A. 1999. Hydrogeology and ecology of clinker in the Powder River Basin, Wyoming and Montana, Coal bed Methane and the Tertiary Geology of the Powder River Basin Wyoming and Montana, Edited by W.R. Miller, Wyoming Geological Association 50th Field Conference Guidebook.

Hem, J.D. 1985, Study and interpretation of the chemical characteristics of natural water (3rd Ed.): U.S. Geological Survey Water-Supply Paper 2254.

Jackson, R.E., Reddy, K.J., Olsen, R.A., and Legg. D.E. 2003. Geochemistry of Coal Bed Methane Product Water Across Five Wyoming Watersheds.

Lamarre, R.A. 2001. The CBM Potential of the Denver Basin, presented to the Denver SPEE, September 28, 2001.

Larson, L.R. 1988, Coal-Spoil and Ground-Water Chemical Data from Two Coal Mines; Hanna Basin and Powder River Basin, Wyoming. U.S. Geological Survey Open-File Report 88-481.

Lawson, John. 2005. U.S. Bureau of Reclamation. Phone correspondence with Bruce Langhus. November 18th, 2005,

Likwartz, Don. 2005. Wyoming Oil and Gas Conservation Commission. Phone Correspondence with Bruce Langhus (ALL Consulting). October 27th, 2005.

Martin, Lawrence J., David L. Naftz, H.W. Lowham, and J.C. Rankl. 1988. Cumulative Potential Impacts of Surface Coal Mining in the Eastern Powder River Structural Basin, Northeastern Wyoming. U.S. Geological Survey Water Resource Investigations Report 88-4046, Cheyenne, Wyoming 1988.

Mazunder, Saikat, Karl-Heinz A., and A. Wolf. 2003. CO2 Injection for Enhanced CH4 production from Coal Seams: Laboratory Experiments and Simulations. Proceedings PETROTECH-2003, New Delhi.

McKinley, Mike. 2004. BLM Buffalo Field Office. Phone correspondence with Bruce Langhus (ALL Consulting). March 16th, 2004.

Montana Board of Oil and Gas Conservation. 2004. Montana Board of Oil and Gas Conservation, oil and gas website: http://bogc.dnrc.state.mt.us/

Moreland, J.A. 1987. Ground-Water Study 8, in Ground-Water Information Manual: Coal Mine Permit Applications – Volume II, Edited by Richards, David B., U.S. Department of the Interior – Office of Surface Mining Reclamation and Enforcement, pgs. 257-298.

Naftz, D.L. 1990. Geochemistry of batch-extract waters derived from spoil material collected at the Cordero coal mine, Powder River Basin, Wyoming; U.S. Geological Survey Water-Resources Investigations Report 87-4200.

National Oceanic and Atmospheric Agency. 2004. Climate records website: http://www.ncdc.noaa.gov/oa/climate/research/cag3/NA.ht

National Research Council, 1990. Surface Coal Mining Effects on Ground Water Recharge; with Committee on Ground Water Recharge in Surface-Mined Areas, Water Science and Technology Board, Commission on Engineering and Technical Systems; National Academy Press, Washington, D.C.

Northern Plains Resource Council. 2004a. Technology-Based Effluent Limitation for Coal Bed Methane-Produced Wastewater Discharges in the Powder River Basin of Montana and Wyoming, Northern Plains Resource Council, August, 2004.

Northern Plains Resource Council. 2004b, Coal Bed Methane-Produced Water: Management Options for Sustainable Development, Northern Plains Resource Council, August, 2004.

Olson, Joe. 2005. Personal correspondence with Bruce Langhus (ALL Consulting) November 8th, 2005. Williams Production.

Palmer, I.D. and H. Varizi. 2004. Permeability Changes in a CBM Reservoir During Production: An Update and Implications for CO2 Injection. 2004 International CBM Symposium, Univ. of Alabama, May, 2004.

Peterson, Erich, PhD. 1997. Introduction to the Properties of Clay Minerals. http://www.mines.utah.edu/~wmep/30897/30897pdf/lab10.pdf

Rice, C.A., Ellis, M.S., and Bullock, J.H., Jr. 2000, Water co-produced with coalbed methane in the Powder River Basin, Wyoming: preliminary compositional data, U.S. Geological Survey Open-File Report 00-372.

Ringen, B.H. and Daddow, P.B. 1989. Hydrology of the Powder River Alluvium Between Sussex, Wyoming, and Moorhead, Montana, U.S. Geological Survey Water-Resources Investigations Report 89-4002, 53 p.

Rosgen, David L. 1994. A classification of natural rivers. http://www.geo.wvu.edu/~kite/CLASS_OF_NATURAL_RIVERS_300.pdf

Schneider, Thomas J. 2001, Coal Bed Methane Produced Water Reinjection, Northern Plains Research Council, May 15, 2001.

Tudor, M.S. 1975. Geologic exploration and development of coal in the Sarpy Creek area, Big Horn County, Montana, in J. Doroshenko, W.R. Miller, E.E. Thompson, Jr., J.H. and Rawlins, eds., Energy Resources of Montana: Montana Geological Society 22nd Annual Publication, pp. 159-164.

U.S. Army Corps of Engineers. 1982. Engineer Manual 1110-2-2300, Earth and Rock Fill Dams – General Design and Construction Considerations. Revised July 31, 1994.

U.S. Bureau of Reclamation. 2003. Desalting Handbook for Planners, US Bureau of Reclamation Desalination and Water Purification Report #72, 3rd Edition, July 2003.

U.S. Department of Agriculture. 2005. Montana Landuse website: http://www.nass.usda.gov/mt

U.S. Department of Agriculture and National Resource Conservation Service. 1982a. Technical Release No. 60, 210-VI – Earth and Dam Reservoirs. Revised October 1985.

U. S. Department of Agriculture and National Resource Conservation Service. 1982b. Agriculture Handbook Number 590, Ponds – Planning, Design, Construction. Revised 1997.

U.S. Department of Agriculture and National Resource Conservation Service. 2004. The PLANTS Database, Version 3.5 (http://plants.usda.gov). National Plant Data Center, Baton Rouge, LA 70874-4490 USA.

U.S. Department of Interior. Bureau of Land Management (BLM). 1999. Wyodak Coal bed Methane Project Final EIS, Buffalo Field Office. October 1999.

U.S. Department of Interior. Bureau of Land Management (BLM). 2001. Williston Basin for potash lignite oil and gas.

U.S. Department of Interior. Bureau of Land Management (BLM). 2003a. Final Environmental Impact Statement and Proposed Plan Amendment for the Powder River Basin Oil and Gas Project, Buffalo Field Office, WY-070-02-065

U.S. Department of Interior. Bureau of Land Management (BLM). 2003b. Final Statewide Oil and Gas Environmental Impact Statement and Proposed Plan Amendment for the Powder River and Billings Resource Management Plans, Miles City & Billings Field Office and State of Montana, BLM/MT/PL-03/005

U.S. Environmental Protection Agency (EPA). 1975. Manual of Water Well Construction Practices: Office of Water Supply, EPA570/9-75-001.

U.S. Environmental Protection Agency (EPA). 1991. Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells: Office of Research and Development, EPA/600/4-89/034.

U.S. Fish and Wildlife Service. 2000. Region 6 River Restoration Program Overview.http://www.r6.fws.gov/pfw/r6pfw2h.htm

U.S. Geological Survey. 1986. Hydrology of Area 50, Northern Great Plains and Rocky Mountain Coal Provinces, Wyoming and Montana, Water Resources Investigations Open-File Report 83-545.

U.S. Geological Survey. 2000. Produced Water with Coal-Bed Methane, United States Geological Survey Fact Sheet FS-156-00.

U. S. Geological Survey. 2001. Estimated use of water in the Unite States. USGS website: http://water.usgs.gov/watuse/

U.S. Geological Survey. 2002. Application of Airborne Hyperspectral Data to Soil Irrigation Suitability in Areas of Coalbed Methane Development, Powder River Basin, Montana. http://rockyweb.cr.usgs.gov/public/html/cbmsoils\

Wagner, John. 2005. Administrator Water Quality Division WDEQ. Personal correspondence with Bruce Langhus (ALL Consulting). November 1st, 2005.

Wheaton, John and Brown, Terry. 2005, Predicting changes in ground-water quality associated with coalbed methane infiltration ponds, in Western Resources Project Final Report – Produced Groundwater Associated with Coalbed Natural Gas Production in the Powder River Basin, editor Mark D. Zoback, Wyoming State Geological Survey, Report of Investigations No. 55.

Wheaton, John R., Bobst, Andrew L. and Brinck, Elizabeth L. 2007. Considerations for Evaluating Coalbed Methane Infiltration Pond Sites, Based on Site Studies in the Powder River Basin of Montana and Wyoming. Paper presented at the 2007 National Meeting of the American Society of Mining and Reclamation, Gillette, WY.

Wyoming Department of Environmental Quality, Water Quality Division. 2005. Memorandum, Revisions to Off-channel Unlined CBM Produced Water Pit Siting Guidelines for the Powder River Basin, Wyoming, dated August 6, 2002.

Wyoming Department of Environmental Quality, Water Quality Division. 2004. Compliance Monitoring for Ground Water Protection Beneath Unlined Coal bed Methane Produced Water Impoundments.

Wyoming Department of Environmental Quality, Water Quality Division. 2002. Off-Channel, Unlined CBM Produced Water Pit Siting Guidelines for the Powder River Basin, Wyoming.

Wyoming Oil and Gas Conservation Commission. 2004. Oil and Gas website: http://wogcc.state.wy.us/

APPENDICES

APPENDIX A - Maps

APPENDIX B - Borehole Lithologic Logs, Well Construction Diagrams, and Geophysical Logs

APPENDIX C - Cross Sections

APPENDIX D - Calculations

APPENDIX E - Groundwater Discussion

APPENDIX F - Groundwater Figures