Coalbed Methane Stream Depletion Assessment Study – Northern San Juan Basin, Colorado

Prepared for:

State of Colorado Department of Natural Resources, Division of Water Resources and the Colorado Oil and Gas Conservation Commission

Prepared by:

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In Conjunction with:

Colorado Geological Survey
Denver, Colorado

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EXECUTIVE SUMMARY

The San Juan Basin is the most productive source of coalbed methane (CBM) in North America. Typically, in conjunction with the production of CBM is the production of water. In the San Juan Basin in Colorado there are concerns with the amount, quality, uses, and effects of CBM produced water and with how the production of water may be affecting CBM gas seepage at the surface. Specific to this study, there are concerns that the removal of water from aquifers that may be tributary to the surface stream system could be resulting in stream depletions or reductions in spring flows that could potentially impact water rights holders, the State of Colorado, and downstream water users not in Colorado. For these reasons it was considered important both to evaluate the extent and impacts of CBM water production in the San Juan Basin and to assess the regulatory framework associated with the production of CBM water, the potential for beneficial uses of such water, and the interstate ramifications of the consumptive uses of such water.

To promote communication and facilitate this evaluation of conditions in the San Juan Basin in Colorado, a public meeting was advertised and held in Durango on October 24, 2005. The meeting was held for the purpose of informing interested parties of the nature of the study and to solicit input and comments that might be of value to the study team. Comments provided to the study team are included in the report and were considered by the study investigators.

While the production of CBM in Colorado and disposal of associated exploration and production wastes, including produced water, is regulated by the Colorado Oil and Gas Conservation Commission (COGCC), the State Engineer's Office, Division of Water Resources (DWR), has jurisdiction over the removal of groundwater that is put to beneficial use. Because of the joint interest of the COGCC and the DWR in ensuring efficient production of CBM and in protecting the state's water resources, the two agencies embarked on this study as a cooperative effort. The primary objectives of this CBM study were:

- To provide an overview of the geographic, geologic, hydrologic, water quality and regulatory setting in the Colorado portion of the San Juan Basin as it relates to the production of CBM and CBM produced water;

- To implement and evaluate the suitability of a stream depletion analytical tool, the Glover analysis (Glover and Balmer, 1954), to administer CBM water production in the San Juan Basin; and,

- To develop a quantitative assessment of the levels of stream depletion or reduction in formation outflows that may be occurring as a result of the removal of water by CBM wells.

CBM in the San Juan Basin is produced primarily from the coals in the late Cretaceous Fruitland Formation. For this study, which was primarily concerned with the production of water from CBM wells, the Fruitland Formation and the adjacent Pictured Cliffs Sandstone were considered to form a low permeability aquifer referred to informally as the Fruitland-Pictured Cliffs aquifer. In Colorado, the extent of the Fruitland-Pictured Cliffs aquifer is defined by the

well-delineated outcrop of the Fruitland Formation and Pictured Cliffs Sandstone along the northern boundary of the San Juan Basin.

A stream depletion analysis for approximately 1,650 Fruitland Formation CBM wells in the San Juan Basin was conducted to quantify current and expected future depletions of surface water due to CBM-related groundwater extraction. While the hydrology of the basin and the Fruitland-Pictured Cliffs aquifer do not obviously suggest the application of the Glover solution for stream depletion analysis, using a conceptual model that related the Fruitland-Pictured Cliffs aquifer to the aquifer outcrop and the streams traversing the basin provided a useable first-order determination of depletion for most of the area within the basin in Colorado. The method was not fully applicable in the highly productive Fairway region where the Fruitland-Pictured Cliffs aquifer may not be water saturated. To estimate depletion in this area, a different methodology would be required.

The current CBM water production rate in the San Juan Basin in Colorado is approximately 3,000 ac-ft/yr. According to the modeling, the depletion as of August 2005 for the CBM wells within the basin in Colorado was determined to be about 155 ac-ft/yr. This quantity does not differ greatly from the depletions calculated in the 2001 3M models—95 to100 ac-ft/yr for projections for 2005 for the Animas, Florida, and Los Pinos Rivers (Cox et al., 2001)—particularly given that those models did not include the entire CBM production area. Based on assumptions for the water production for CBM wells in the San Juan Basin, the depletion rate for existing wells will peak in about 2020 at slightly above 160 ac-ft/yr, and by 2070, depletions will drop below 100 ac-ft/yr. Under a buffered future well scenario (i.e., no wells within 1.5 miles of the outcrop), depletions were estimated to peak in 2035 at approximately 170 ac-ft/yr, and would drop below 100 ac-ft/yr by 2150. Beyond 2150, depletions continue to drop slowly, but do not go below 50 ac-ft/yr until about 2300. If CBM wells were to be installed within 1.5 miles of the outcrop, depletions would peak in about 2025 at over 500 ac-ft/yr. However, by 2150 depletions would be roughly equal to the buffered scenario.

The results of the stream depletion analysis were considered in conjunction with statutory criteria for delineation of a nontributary area, wherein the withdrawal of groundwater by a well will not, within 100 years, deplete the flow of a natural stream at an annual rate greater than one tenth of one percent of the annual rate of withdrawal. Where the Glover analysis was considered to provide a useable estimate for depletion, areas in the San Juan Basin greater than approximately 10.5 miles from the Fruitland-Pictured Cliffs outcrop fall within the nontributary area.

In Colorado, CBM produced water, like water produced from any other type of oil or gas well, is handled as waste by COGCC Rule 907, and it remains under the jurisdiction of the COGCC. However, if CBM produced water is put to a beneficial use beyond the uses allowed under Rule 907, it is subject to DWR regulation through a permitting process and water users are subject to various controls to avoid injury to vested water rights. In some cases, augmentation of depletions to streams may be required.

In the San Juan Basin most CBM produced water is disposed by injection into Class II UIC wells that are regulated by COGCC on lands north of the Southern Ute Indian Tribe (SUIT) line and by EPA south of the SUIT line. In cases where the disposal involves discharge to the waters of the state, a permit must be obtained from the Colorado Water Quality Control Division.

While the regulatory framework may appear complicated, the authority and guidance to put CBM water to beneficial use are well established.

Very little CBM water is used for beneficial purposes, in part because the quality of the water in the Fruitland-Pictured Cliffs aquifer in most of the Colorado portion of the San Juan Basin is too poor for most uses that involve a sizeable and relatively continuous supply of water. In addition, because of the relatively low demand for water for local municipal and industrial supply purposes, it is unlikely that the construction of the necessary infrastructure to treat/transfer water to points of use in the basin will be economically feasible in the near future.

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April 4, 2006

Interested Parties

Re: Coalbed Methane Stream Depletion Assessment Study – Northern San Juan Basin, Colorado

Dear Ladies and Gentlemen:

The report dated February 2006 prepared by S.S. Papadopulos & Associates, Inc. is provided for public review and comment. This study was a joint effort by the Colorado Oil and Gas Conservation Commission ("COGCC"), the Colorado Geological Survey ("CGS") and the State Engineer's Office Division of Water Resources ("DWR"). These agencies are part of the Colorado Department of Natural Resources ("DNR").

The purpose of this study was to develop a quantitative assessment of the levels of stream depletion or reduction in formation outflows (spring flows or flowing stream systems gaining from contact with formations) that may be occurring as a result of the removal of water by coalbed methane wells. This water historically has been disposed by one or more methods, including re-injection into deep formations, discharge to the surface stream system, and ponding/evaporation. The concern has been raised that the removal of ground water from aquifers that may be tributary to the surface stream system could be resulting in stream depletions or a reduction in spring flows and/or formation outflows (accretions) that are of a magnitude sufficient to cause injury to senior water rights holders on over-appropriated stream systems. This study sought to develop a reliable assessment as to the levels of depletion, definition of the areas where CBM is ongoing that might be classified as nontributary, definition of any potential correlations of water quality, geology, aquifer geometry, or formation/well depth

that could lead to general guidelines about the potential for stream depletion that would be useful in either prompting or avoiding more detailed studies, and development of recommendations for further data collection or investigations.

The results of this study indicate that depletion estimates are relatively low compared to flows in the rivers. The combined mean yearly base flows for the Animas, Florida and Pine Rivers average nearly 227,000 ac-ft/yr while the current depletion as of August 2005 was estimated to be 156 ac-ft/yr. Even though the current amount of depletion estimated by this study occurs year-round, the amount of depletion that occurs during a time of surface water administration (i.e., senior water right placing call on a stream system) is less since active surface administration only occurs on average 110 days. Additionally, some of the streams within the San Juan Basin are not currently over appropriated (e.g., Animas River) and, therefore, not under administration. When these conditions are considered, the amount of depletion from CBM production that occurs during these conditions is less than 50 ac-ft/yr.
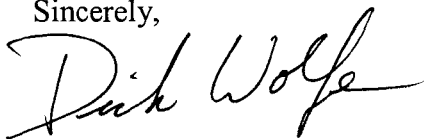
For perspective, the amount of stream depletion associated with CBM well production in the San Juan Basin estimated by this study can be compared to the amount of stream depletion associated with an equivalent number of exempt domestic wells on an equivalent spacing. The current spacing for CBM wells in the San Juan Basin is assumed to average 160 acres. For exempt domestic wells, one well could be issued on every 35 or more acre tract of land. The amount of stream depletion associated with a typical exempt well in this area on a 35 or more acre tract is approximately 0.6 ac-ft/yr (one single-family dwelling, 10,000 square-feet of lawn and garden and four large animals). It is assumed for purposes of this analysis that all of the stream depletion associated with the CBM wells occurs from the wells within approximately ten miles of the outcrop, which represents the area for wells outside of the estimated nontributary area. This area represents approximately 1000 CBM wells and over 427,000 acres. An equivalent number of exempt domestic wells would result in approximately 600 ac-ft/yr of stream depletions. If all 427,000 acres were developed with exempt wells, one well on each 160-acre tract, there would be approximately 2,670 exempt domestic wells. The amount of stream depletion associated with these 2,670 wells would be approximately 1,600 ac-ft/yr. Thus, the

amount of potential stream depletion associated with exempt wells that could be developed in this area is over nine times the estimated maximum annual depletion from CBM production. One must also consider that the average life of one CBM well is approximately 20 years while the production life for an exempt well is potentially perpetual.

DNR strives to promote an open and honest communication that builds trust and respect with those we serve. This fosters continuous improvements and innovative thought, learning and shared leadership. The success of this study depends on the involvement of those in the industry who develop and produce gas and oil resources in Colorado with DNR and its respective agencies. Therefore, we would appreciate any comments regarding this study by **Wednesday, May 3, 2006**. Comments can be sent to my attention at the above address or by email at dick.wolfe@state.co.us.

A copy of the study is available for viewing at the Colorado Division of Water Resources website at: www.water.state.co.us. Thank you for participating in this process. A public meeting will be held in Durango in June to discuss the results of this report and any comments received. More details will follow once the meeting time and place have been determined.

Sincerely,

Dick Wolfe, P.E.

Assistant State Engineer

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1.0   INTRODUCTION

1.1   <u>Background</u>

The San Juan Basin is the most productive source of coalbed methane (CBM) in North America. Estimated CBM reserves for the basin, which extends from southwest Colorado into northwest New Mexico (Figure 1.1), are nearly 50 trillion cubic feet (Tcf) of gas in place (Ayers, et al., 1994). Since the initial production of CBM in the basin in the mid 1980s, over 11 Tcf of gas have been produced from the basin. CBM production from the approximately 1,650 wells drilled in Colorado exceeds 4.2 Tcf through July 2005.

In conjunction with the production of CBM is the production of water. In contrast to traditional oil and gas wells where water is generally produced in highest quantities during the later portion of a well's life as the hydrocarbon production is falling off, in CBM wells water production is normally greatest immediately after the well is brought on line. Later, as water production declines, CBM production increases. This pattern occurs because CBM is sorbed on the surfaces of the coal itself and is held in place by the hydrostatic pressure of the water that fills the fractures (known as cleats) of the coal. As water is pumped out of the coal-bearing formation and the pressure in the formation drops, the gas desorbs from the coal into the cleats and migrates into the well where it is captured at the ground surface. Eventually, as pressure and water production decline, gas production increases and a well may have a long productive period with relatively high gas production and little to no water production. The production curves shown in Figure 1.2 for three San Juan Basin CBM wells, while distinctly different from each other, clearly illustrate this pattern.

There are concerns with the amount, quality, uses, and effects of CBM produced water in the San Juan Basin in Colorado and with how the production of water may be affecting CBM gas seepage at the surface. Specific to this study, there are concerns that the removal of water from aquifers that may be tributary to the surface stream system in the San Juan Basin could be resulting in stream depletions or reductions in spring flows that could cause injury to senior water rights holders.

While the production of CBM in Colorado and disposal of associated exploration and production waste, including produced water, is regulated by the Colorado Oil and Gas

Conservation Commission (COGCC), the State Engineer's Office, Division of Water Resources (DWR), has jurisdiction over the removal of groundwater that is put to beneficial use. In addition, the U.S. Environmental Protection Agency (EPA) regulates Class II injection wells used for the disposal of produced water on the Southern Ute Indian Tribe (SUIT) lands. Because of the joint interest of the COGCC and the DWR in both ensuring efficient production of CBM and in protecting the state's water resources, the two agencies (with assistance from the Colorado Geologic Survey [CGS]) are embarking on a study to evaluate the magnitude of stream depletions from CBM production and whether a relatively simple analytical tool can be used to administer CBM water production where required. To address the concerns mentioned above, this initial study addresses the conditions in the San Juan Basin.

1.2 Objectives

The primary objectives of this CBM study are:

- To provide an overview of the geologic, hydrologic, water quality and regulatory setting in the Colorado portion of the San Juan Basin as it relates to the production of CBM and CBM produced water;

- To implement and evaluate the suitability of a stream depletion analytical tool, the Glover analysis (Glover and Balmer, 1954), to administer CBM water production in the San Juan Basin; and,

- To develop a quantitative assessment of the levels of stream depletion or reduction in formation outflows (spring flows or flowing stream systems gaining from contact with formations) that may be occurring as a result of the removal of water by CBM wells.

1.3 Scope of Work

CBM in the San Juan Basin is produced primarily from the coals in the Cretaceous age Fruitland Formation. The extent of the Fruitland Formation in Colorado is defined by the well delineated outcrop of the formation along the northern boundary of the San Juan Basin. This study examines existing information relating to the geographic setting, geology, hydrogeology, CBM gas and water production, and water chemistry of the Fruitland and adjacent formations. Existing information was obtained from the DWR, COGCC, CGS, United States Geological Survey (USGS), and other public domain sources.

A public meeting was advertised and held in Durango on October 24, 2005, as part of this study. The meeting was held for the purpose of informing interested parties of the nature of the study and to solicit input and comments that might be of value to the study team. Comments provided to the study team are included in Appendix A and were considered by the study investigators.

A stream depletion analysis for approximately 1,650 Fruitland Formation CBM production wells in the San Juan Basin was conducted to quantify current and expected future depletions of surface water due to CBM groundwater extraction. This analysis used an automated parameter estimation procedure to identify best estimates for aquifer parameters using historical pumping and pressure data. The results of the stream depletion analysis are considered in conjunction with statutory criteria for delineation of a nontributary area, wherein the withdrawal of groundwater by a well will not, within 100 years, deplete the flow of a natural stream at an annual rate greater than one tenth of one percent of the annual rate of withdrawal. The study further examines regulatory and other issues regarding use of CBM produced water.

The goal of this study is to provide background regarding CBM production and to evaluate associated CBM produced water stream depletions. As such, there are many related topics or analyses that fall beyond the scope of this study. Topics not evaluated as part of this study include:

- Reservoir optimization, i.e., production or well spacing issues;
- Dual-phase flow dynamics;
- Historical conditions and climatic influences on streams and springs;
- Impacts of other basin extraction activities on streams or water levels; and
- Evaluation of localized groundwater elevation changes at specific sites.

That the above topics are not included in this study is not a reflection of their importance; rather, it is a reflection of the focus of this study on evaluation of stream depletion.

1.4   Available Data and Resources

For the most part, this study draws on existing data and studies to provide an overview of conditions in the basin and to provide well information and CBM and water production data. Analysis of depletion similarly relies on existing data; however, while the estimation of aquifer parameters necessary to perform the Glover analysis considers existing studies, the values of the

parameters determined for input into the analysis were determined independently of those studies. The studies and datasets used to produce this study report are described below.

1.4.1   Geographic and Geologic Data

A large electronic GIS-based dataset is available that provides physical and political geographic information for the San Juan Basin. The region's topographic, hydrographic, and cultural details were obtained from public domain sources accessible by internet and from GIS datasets maintained by the CGS and the COGCC. Included in the CGS dataset were detailed information for the geologic outcrops of the formations of interest and the drainages that cross into the San Juan Basin.

1.4.2   Well and Production Data

Oil, gas, and CBM well and production data is systematically collected by the COGCC. Much of their database is available for browsing on the internet at http://oil-gas.state.co.us. For this study, the complete dataset extending back to 1999 was obtained from the COGCC. Additionally, the 3M reservoir modeling study performed by Questa Engineering (Questa, 2000) included assembly of CBM gas and water production data extending back to 1985, the time of initial CBM production in the San Juan Basin, in electronic format. These data were obtained from the COGCC website at http://oil-gas.state.co.us/Library/SanJuanBasinReports.htm and merged with the COGCC dataset to produce a substantially complete record of production in the basin through July 2005.

The primary dataset used for the Glover depletion analysis was the monthly gas and water production assembled by the COGCC and Questa. In addition to providing gas and water production data, the database also provided well completion details, initial pressure data, and in a few cases subsequent pressure data. Pressure data from several CBM monitoring wells were provided by COGCC. Including four production wells, records for 19 wells with continuous pressure measurements were provided.

1.4.3   Aquifer Characteristics

Estimates for Fruitland coal aquifer characteristics (porosity, permeability, storativity) are not abundantly available in the literature. Estimates of permeability are occasionally provided

(e.g., Kaiser et al., 1994), however, no detailed studies are known to be publicly available. A small number of shut-in test results that provide transient pressure data have been extracted from the well and production dataset assembled for this study. Groundwater and reservoir models constructed in the basin (Kaiser et al., 1994; Kernodle, 1996; Applied Hydrology Associates [AHA], 2000; Questa, 2000; and Cox et al., 2001) provide estimates of permeability and storativity for the Fruitland Formation as developed in those investigations.

1.4.4 Stream and Spring Flow Data

Information on the locations of springs and seeps associated with the Fruitland Formation are provided in the Draft Environmental Impact Statement (EIS) for the portion of the San Juan Basin north of the Southern Ute Indian Tribe (SUIT) Reservation (BLM, 2004). Additionally, the CBM producers and the COGCC are currently involved in an effort to gain information on the locations and flows of springs and seeps that occur in and adjacent to the Fruitland Formation and Pictured Cliffs Sandstone and in the alluvium covering them.

1.4.5 Water Quality Data

Major ion water chemistry and total dissolved solids (TDS) are the primary parameters used to evaluate disposition options for CBM produced water. In the San Juan Basin the majority of the water is re-injected because it is the most environmentally sound method to dispose of this waste. Major ion chemistry can be useful for evaluating the sources and rates of travel of groundwater in the Fruitland aquifer system. Primary water quality data were not assembled as part of this study; however, existing characterizations of water quality were reviewed. Similarly, existing characterizations of isotope chemistry were reviewed as they have been found useful by some investigators in examining sources of water and flow pathways and estimating groundwater ages within the San Juan Basin.

1.4.6 Future Coalbed Methane Production Estimates

A single scenario for future CBM production was prepared for this study based on information provided in the 3M modeling efforts (AHA, 2000; Questa, 2000), COGCC well spacing orders for the San Juan Basin, which are available on the COGCC website at http://oil-gas.state.co.us/, review of scenarios presented in the Draft EIS (BLM, 2004), and discussion with

COGCC personnel. This scenario provides a reasonable representation of a future condition for the purposes of this analysis.

1.5   Report Organization

Chapter 1 provides introductory material and a summary of data sources. Chapters 2 through 5 discuss the physical setting of the basin, the geologic and hydrogeologic characteristics of the Fruitland Formation and the adjacent Pictured Cliffs Sandstone, and San Juan Basin CBM gas and water production. Chapter 6 describes the stream depletion analysis. Chapter 7 provides a regulatory overview including a discussion of potential beneficial uses of CBM produced water and implications for CBM water production on interstate stream compacts. Chapter 8 summarizes results and conclusions and makes recommendations for further analysis in the San Juan Basin and other CBM-producing basins in Colorado.

2.0   NORTHERN SAN JUAN BASIN GEOGRAPHIC SETTING

2.1   Topography

The San Juan Basin covers an area of approximately 6,700 mi^2 of the east-central Colorado Plateau. Approximately 800 mi^2 of this vast basin extends into southwestern Colorado in an area characterized by badlands, mesas, and hogbacks held up by resistant sandstone formations dipping toward the basin center. The northern boundary of the San Juan Basin is clearly defined by the prominent hogback outcrop of the Cretaceous Pictured Cliffs Sandstone. Elevation at the northern end of the basin along the hogback reaches a height of almost 9,000 ft above mean sea level at Vosburg Pike and drops to approximately 6,000 ft at the New Mexico-Colorado border where the major stream systems flow from Colorado into New Mexico.

The topographic setting of the San Juan Basin influences precipitation patterns which, in turn, have an effect on groundwater recharge to the aquifers within the basin. Just north of the basin rise the San Juan Mountains which orographically catch moisture driven from the Pacific Ocean by the prevailing westerly jet stream. With this geographic setting, annual precipitation along the elevated hogback rim of the northern San Juan Basin can be as high as 24 to 28 inches (Figure 2.1) supporting dense conifer forests. Annual precipitation in the lower parts of the basin is about half as much, ranging between 12 and 14 inches.

2.2   Surface Drainage Basins

Five major streams, sourced from headwaters high in the San Juan Mountains to the north, enter the San Juan Basin and converge to form the San Juan River in New Mexico. Further to the west, the San Juan River joins the Colorado River at Lake Powell in southeastern Utah. The main streams crossing the hogback rim of the northern San Juan Basin are shown in Figure 2.2 and include, from west to east: the Animas River, the Florida River, Los Pinos River, the Piedra River (along with Devil and Stollsteimer Creeks); and the San Juan River.

A number of tributaries to these streams have headwaters in the hogback region peripheral to the San Juan Basin. Many of these tributaries are either ephemeral or support very low base flow (on the order of 1 cubic foot per second [cfs] or less). Other tributaries arise within the basin itself to join the major river systems as they flow south.

3.0 NORTHERN SAN JUAN BASIN GEOLOGIC SETTING

3.1 Basin Stratigraphy

Although the San Juan Basin contains many sedimentary formations laid down over an extensive period of time, extending from Upper Cambrian, approximately 500 million years ago (Ma) through middle Paleogene (approximately 40 Ma), the coal deposits associated with CBM are found only in the Upper Cretaceous sedimentary sequences deposited along the western shoreline of the Cretaceous Western Interior Seaway (BLM, 1999). The Western Interior Seaway (Figure 3.1) covered large areas of the interior of the North American continent for over 20 million years. The seaway shoreline underwent several episodes of advance and retreat before final withdrawal of the seaway near the end of the Cretaceous (Wray, 2000; Ayers et al., 1994). Figure 3.2 is a time stratigraphic chart of the Upper Cretaceous period that shows the rocks preserved in the northern San Juan Basin in Colorado by two episodes of seaway advance followed by retreat. The marine Mancos Shale and Lewis Shale represent periods of seaway advance. The Mesa Verde Group, which separates the Mancos and Lewis Shales, represents a temporary retreat of the seaway and consists of the Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone. The final retreat of the seaway resulted in the deposition of the Pictured Cliffs Sandstone, Fruitland Formation and Kirtland Shale above the marine Lewis Shale.

It is interpreted that, at the time that the coal-bearing formations were deposited, the environment consisted of barrier bars separating the seaway to the east from extensive swamps to the west (Ayers et al., 1994). Streams originating in the highlands further to the west crossed through the back-bar swamps and flowed into the seaway via distributary channels in wave-dominated deltas. Each time the seaway retreated to the east, beach and delta sands buried the offshore marine shales. Subsequently, vast peat deposits, containing abundant coal-forming plant debris, collected in the back-bar swamps and in turn, buried the beach and delta sands. Fluvial stream sands combined with over-bank silts and clays eventually buried the back-bar peat deposits. Other peat deposits were also formed in smaller swamps developed along the river systems further to the west.

At any particular point in time, a barrier bar and an associated back-bar swamp may have been several miles wide; however, since the shoreline was slowly migrating to the east as the basin subsided, the deposits preserved eventually became very extensive, covering many tens or hundreds of miles across the region. Formations deposited over a long period of time in this manner are time-transgressive. During periods of seaway advance to the west, deposits such as the Cliff House Sandstone (Figure 3.2), become younger to the west; while formations deposited during seaway retreat to the east (shoreline progradation), such as the Pictured Cliffs Sandstone become younger to the east.

Following the final retreat of the Western Interior Seaway, continental sedimentation continued by river systems flowing to the east across a broad coastal plain depositing the Upper Cretaceous Kirtland Shale. The Kirtland Shale consists of overbank and channel mudstones, siltstones, and sandstones subdivided in the northern San Juan Basin by the fluvial Farmington Sandstone into upper and lower shale units (Carroll et al., 1999). The Laramide Orogeny, which began late in the Cretaceous and extended into the Eocene (70 Ma to 30 Ma), was accompanied by deposition of the Animas Formation, the McDermott Member of the Animas Formation, and the San Jose Formation.

3.2   Basin Structural Geology

The San Juan Basin is an asymmetric structural basin that formed during the Laramide Orogeny. In the deepest part of the basin in northwest New Mexico, Precambrian crystalline basement rocks lie more than 14,000 feet beneath the surface (Laubach, 1994). The Hogback Monocline marks the northern edge of the basin in Colorado and exposes over 5,000 feet of Upper Cretaceous through Paleogene sedimentary rocks (BLM, 1999, Carroll 1999). Dips along the monocline can range between 20 and 50 degrees, but they decrease rapidly into the basin away from the monocline axis (Carroll et al., 1997, 1998, and 1999).

Faulting within the northern part of the San Juan Basin has been identified at a few locations (Tremain et al., 1994); however, published geologic maps and the literature do not indicate that large-scale faulting is present in the basin. The lack of widespread faulting suggests that the basin may be relatively unbroken. Small-scale faults may be much more prevalent but they simply have not been identified and/or published. Fracturing is pervasive in the outcrop

along the monocline and has been identified in the subsurface as an important factor in gas production (Tremain et al., 1994). Fracturing and fracture patterns that may be relevant to CBM development and groundwater flow patterns are discussed in more detail below.

3.3 Coalbed Methane Resources

The San Juan Basin is well known for its economic energy resources that include conventional oil and gas, CBM, and coal. Conventional oil and gas resources have been developed from the Upper Cretaceous Dakota, Point Lookout, Cliff House, and Pictured Cliffs Sandstones. The sources of the hydrocarbons in these formations are probably the marine Mancos and Lewis Shales (BLM, 1999). Economic coal resources are present in the Menefee and Fruitland Formations and have played an important role in the economic development of the region, particularly in the vicinity of Durango (Carroll et al., 1999). Many historic mines can be found along the Hogback Monocline.

Methane has long been known to be present in the coals of both the Menefee and Fruitland Formations (BLM, 1999, Wray, 2000). Figure 3.3 shows the surface outcrop pattern of both the Menefee and Fruitland Formations. The Menefee Formation is limited to the western edge of the basin since the coal-bearing intervals pinch out to the east near Los Pinos River. Methane gas seeps have been recognized emanating from the outcrop, in streams, and in coal mines in both formations since the 1930s, long before the first CBM production in 1951 (BLM, 1999). Methane has historically been a major hazard associated with underground coal mining.

Estimates of CBM gas-in-place are as high as 50 Tcf in the Fruitland Formation and 34 Tcf in the Menefee Formation (BLM, 1999). Even though this vast gas resource has been long recognized, extensive CBM development did not blossom until the mid-1980s following passage of the Crude Oil Windfall Profits Tax Act of 1980. This pivotal act provided tax incentives to overcome technical problems associated with CBM production.

The Fruitland Formation contains the most favorable CBM reservoirs from the standpoint of current technology and economics. Depths to the extensive basal coal seams are relatively shallow (less than 3,500 feet in Colorado except in two small areas) and the hydrologic conditions within these seams have been favorable to development of CBM (Kaiser et al., 1994). Within the Fruitland Formation, the best coal deposits in terms of both net thickness and

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maximum individual coal seam thickness are found in the northwestern portion of the San Juan Basin in the "Fairway" which extends from near the basin edge southwest of Durango through La Plata County southeast into Rio Arriba County, New Mexico.

Whereas significant coal resources and CBM resources may also be present in the older Menefee Formation, only very limited CBM development has occurred. The reasons for limited CBM development potential to date in the Menefee are primarily greater depth and thinner less extensive coal seams (Zapp, 1949). Further, the Menefee coal seams were deposited in a more fluvial environment (Carroll, 1999), in contrast to the barrier-bar swamp environment of the basal Fruitland coal seams. In general, fluvial dominated coal deposits tend to be thinner and less continuous, often pinching out against fluvial channel-fill sand bodies (Ambrose and Ayers, 1994). CBM production may eventually be developed from the Menefee Formation coal deposits.

3.4 Geology of the Fruitland Formation and Pictured Cliffs Sandstone

3.4.1 Stratigraphy and Coal Bed Occurrence

The Fruitland Formation and the Pictured Cliffs Sandstone were deposited along the western edge of the Western Interior Seaway in the late Cretaceous Period as the coastline retreated to the northeast. The units are time-transgressive becoming younger to the northeast. The Pictured Cliffs Sandstone is the coastal facies of the sequence and includes a lower unit consisting of upward coarsening marine mudstone and sandstone interbeds that intertongue with the uppermost Lewis Shale (Figure 3.4). The upper unit of the Pictured Cliffs is composed of stacked sandstone bodies with a composite thickness of 40 to 120 feet interpreted to have been deposited as coastal barrier bars and wave-dominated deltas.

The Fruitland Formation represents the landward continental facies of the Pictured Cliffs coastline and consists of sandstone, mudstone, and coal interbeds. Vast peat deposits collected in swampy environments protected by the barrier bar systems, eventually coalescing into very extensive coal seams following deep burial and compaction. Migration of the Fruitland-Pictured Cliffs shoreline to the east was slow and intermittent, depending on fluctuating sea levels, changing sediment supply, and changes in basin subsidence; as a result, the shoreline shifted back and forth so that the Pictured Cliffs Sandstone and Fruitland Formations intertongue with

each other (Figure 3.4). This relationship is clearly evident in the northern part of the basin in Colorado.

A structural hingeline in the San Juan Basin (shown on Figure 3.5) is believed to have controlled sedimentation patterns during the evolution of the San Juan Basin (Ayers et al., 1994). This feature, which trends east-southeast and is located just south of the Colorado-New Mexico border, is interpreted to be a diffuse zone of complex faulting and fracturing in the interior of the basin. More rapid subsidence of the basin northeast of the hingeline may have driven intermittent shoreline advances during the gradual withdrawal of the Western Interior Seaway as the Pictured Cliffs Sandstone was being deposited. In terms of CBM development, the most favorable coal deposits lie northeast of this hingeline (Ayers et al., 1994). Further, the hingeline appears to have limited the southeast extent of the inter-tonguing of the upper Pictured Cliffs Sandstone and the Fruitland Formation.

The Fruitland Formation is overlain by the Kirtland Shale, which is also believed to be predominantly continental in origin, but does not contain significant coal deposits like the Fruitland Formation. Ayers et al. (1994) place the contact between the Fruitland Formation and the Kirtland Shale at the base of a regionally extensive electrical log high resistivity shale layer that may have formed during a brief return of the marine seaway.

3.4.2   Structural Geology

The Hogback Monocline marks the northern edge of the San Juan Basin and is the dominant structure in the northern basin. However, a number of other structures, or structural elements, may play important roles in controlling groundwater flow in both the primary coal-bearing Fruitland Formation and the underlying Pictured Cliffs Sandstone. Although the direct influence of these structures on groundwater flow are not well understood, or universally accepted, inferences can be made to help understand the regional groundwater flow patterns in this part of the basin. Each type of structure will be described below, ranked in order of interpreted importance to groundwater flow.

Coalbed cleats. Cleats are natural systematic fractures in coal seams (Tremain et al., 1994) believed to have formed soon after coalification. Typically oriented normal to the bedding, cleats are generally open-mode planar features found in subparallel sets with the earliest

formed sets having more continuous length; hence, they are termed "face" cleats. Subsequent cleat sets that terminate against the face cleats are called "butt" cleats. Primary cleats extend across multiple coal-type layers and secondary or tertiary cleats are vertically discontinuous between layers. Spacing between cleats is believed to be a function of coal rank and type, coal seam thickness, structural setting, and stratigraphic position; with a mean primary face cleat spacing in the northern San Juan Basin of 1.5 inches (Tremain et al., 1994).

Fracturing. Natural joint sets have been well documented in the well-indurated sandstones of the Fruitland Formation and the upper Pictured Cliffs Sandstone (Carroll et al., 1998 and 1999; and Condon, 1997). These fractures are believed to have tectonic origins and may be younger than the cleats found in the coal seams. Fracture sets in the northern San Juan Basin fall into two primary sets, referred to as J1 and J2, with J1 being the older and better-developed set. The most prevalent orientation of the J1 fracture sets observed in the Pictured Cliffs Sandstone and Fruitland Formation is north-northwest (Figure 3.6). In areas where both face-cleat orientations in the Fruitland Formation coals and fractures in the Pictured Cliffs Sandstone have been measured, they appear to be nearly the same.

Where seen in outcrop many J1 fractures have prominent iron oxide staining on their faces as well as iron oxide stain banding (Liesigang banding) sub-parallel to the fractures. Although the chemical origin of the iron oxide stains may be complex, the presence of the staining is a strong indicator of water flow through the fractures prior to exhumation.

Igneous dikes. The Tertiary Dulce Dike Swarm passes through the northern San Juan Basin at the eastern end of the Fruitland-Pictured Cliffs outcrop (Figure 3.7). These dikes are near vertical intrusions that probably invaded existing fractures or faults. CBM resources have not been developed in this area and the relationship between the dikes and the Fruitland Formation and Pictured Cliffs Sandstone has not been closely studied. It can be inferred that the dikes can act as both barriers to flow normal to their orientation as well as conduits to flow parallel to their orientation. There may also be lithologic changes to both the coal seams and bounding mudstones and sandstones from heating by cross cutting dikes. Cooper (2005) reports that intrusive bodies can stimulate methane generation from coal seams under favorable conditions.

Faulting.   Large-scale faults displacing the Fruitland Formation and Pictured Cliffs Sandstone do not appear to be present to a great extent in the northern San Juan Basin. Detailed mapping by Carroll et al. (1997, 1998, and 1999) has identified only a few minor faults along the outcrop. Faulting that may be tectonic in origin or due to differential compaction of the coal-bearing sequences after burial has been recognized in the subsurface and in coal mines (Ayers et al., 1994, Ambrose et al., 1994, and Tremain et al., 1994).   Faults can act as barriers to groundwater flow as well as conduits for groundwater flow. Modeling efforts during the 3M project by AHA (2000) and Questa (2000) incorporated both barriers and conduits, inferred to be faults, to explain anomalous model response in several areas. Because of the relative lack of evidence for large scale faulting as seen in the outcrop, faulting is not believed to be a significant factor in controlling regional groundwater flow.

Folding.   The most notable folding that affects the Fruitland Formation and Pictured Cliffs Sandstone is the Hogback Monocline marking the northern edge of the San Juan Basin. The flexure at the base of the monocline appears to be fairly abrupt with dips increasing from less than 15 degrees in the area underlain by the Animas Formation to greater than 50 degrees where the Pictured Cliffs outcrops (Carroll et al., 1997, 1998, and 1999) over a distance of two miles, or less. The style of folding that formed this structure may have resulted in fracturing along the axis of the fold; however, primary fracture sets along the axis of the monocline were not documented during detailed mapping by the CGS (Carroll et al., 1997, 1998, and 1999).

Within the northern San Juan Basin the Fruitland Formation and Pictured Cliffs Sandstone are folded by a sequence of gentle southeast trending anticlines and synclines with structural relief of a few hundred feet or less. The most prominent of these features are the Ignacio and Bondad Anticlines (Ayers et al., 1994). The Ignacio Anticline plunges southeast towards the deepest portion of the basin. The Hogback Monocline and the Ignacio Anticline and related folds generally corresponds with the highest rank coals in the basin, indicating coincident coalification and fold development related to the Oligocene emplacement of the San Juan Mountains to the north.

3.4.3   Outcrop Areas

The Fruitland Formation and Pictured Cliffs Sandstone outcrop in a belt along the Hogback Monocline that extends in an arc nearly 85 miles from the New Mexico-Colorado border north of Farmington, New Mexico, to the New Mexico-Colorado border south of Pagosa Springs, Colorado (Figure 3.3).   Throughout this extent of the outcrop the total stratigraphic thickness varies considerably, while dips on the top of the Pictured Cliffs Sandstone range between 5 and 53 degrees. As a result, where exposed, the map width of the outcrop is variable, ranging from approximately one tenth of a mile to over two miles. Elevation ranges from almost 9,000 ft above mean sea level at Vosburg Pike between Florida River and Los Pinos River to approximately 6,100 ft near the border with New Mexico. Exposure is generally good, allowing easy identification; however details are often obscured by colluvium, local landslide deposits, terrace deposits, and alluvium along the main stream drainages.

The massive upper sand unit of the Pictured Cliffs Sandstone forms prominent outcrops that are one of the dominant ridge-forming units along the Hogback Monocline. Describing and measuring the thickness of this unit in the field is relatively straightforward over much of the outcrop. The Fruitland Formation, on the other-hand, does not form prominent outcrops and detailed description often requires some type of excavation such as road cuts, ditch cuts, or mines.   Differentiating the intertongues of Pictured Cliffs Sandstone within the Fruitland Formation or, visa-versa, can be difficult in the outcrops and is facilitated by correlations of nearby geophysical logs (e.g., Wray, 2000).

To date, detailed surface geologic mapping has not been completed over the entire length of the outcrop in Colorado. Efforts by the CGS and USGS have focused along the north-central part of the outcrop near the most extensive CBM development and where land use pressures in La Plata County have grown, as well as on the southwestern outcrop on SUIT Reservation lands (Carroll et al., 1997, 1998, and 1999; Carroll and Tremain-Ambrose; 1999; Robinson-Roberts and Uptgrove, 1991).   Additionally, detailed measured sections along the outcrop have been provided by Wray (2000) for the northern part of the outcrop in La Plata County. The eastern segment, where the outcrop extends into Archuleta County and southeast back onto the SUIT Reservation, remains to be mapped in detail.   In this area the Kirtland Shale, Fruitland

Formation, and Pictured Cliffs Sandstone are mapped as an undifferentiated unit by Steven et al. (1975).

Measured sections from these mapping efforts have been compiled in cross section format in Figure 3.8, which illustrates the critical stratigraphic features of the Fruitland Formation coal-bearing interval as well as its relationship with the Pictured Cliffs Sandstone. Geophysical logs from gas wells near the outcrop have also been used in preparing this cross-section where measured sections are absent or do not cover the entire stratigraphic thickness of the Fruitland Formation. The important features evident in the cross-section include: 1) the interpreted lateral extensiveness of the basal coal seams, 2) overlap relationships of successive basal coal seams, and 3) the intertonguing relationship of the Fruitland Formation coal seams with the upper Pictured Cliffs Sandstone. It should also be noted that the Fruitland Formation stratigraphy separating the coal seams has been undifferentiated in this cross-section; however detailed measured sections show that this part of the stratigraphy includes interbedded mudstones, siltstones, and sandstones.

Table 3.1 summarizes features obtained from the measured sections and geophysical logs from select boreholes near the outcrop of the sequence that are relevant to this study including: 1) thickness of the coal-bearing interval, 2) number of coal seams within the interval, 3) net coal thickness, and 4) separation of the lower-most coal from the Pictured Cliffs Sandstone.

Data from geophysical logs are included in Table 3.2 because many of the measured sections traversed segments of the stratigraphy where exposure is poor due to cover or lack of access. When comparing outcrop descriptions and measurements with interpretations of geophysical logs, the following aspects need to be taken into consideration:

- **Thickness.** Geophysical logs provide very accurate measurements of unit thickness; however, the thicknesses must be corrected for bedding plane dip, and in deviated boreholes, for borehole inclination. True stratigraphic thickness for the geophysical logs used to construct Table 3.1 were corrected assuming the boreholes were vertical and using the nearest structural dip measurements from the surface mapping.

- **Coal Identification.** Outcrop exposure provides unambiguous identification of coal lithologies, whereas geophysical log identification of coal is made using bulk density. Wray (2000) used a cut-off of 2.0 grams per cubic centimeter (g/cc) to differentiate coal with the qualification that, at this cut-off, carbonaceous shale

will be included as coal. Because of this, net coal thicknesses from the geophysical logs may be biased high relative to thicknesses from outcrop measured sections. Wray (2000) concludes, however, that the carbonaceous shales may contribute methane to the CBM production so their inclusion is valid. For this overview study the issue of coal-carbonaceous shale identification is not critical.

3.4.4 Characteristics Bearing on Coalbed Methane Production

Many important geologic features make the Fruitland Formation coals favorable for CBM development (Kaiser and Ayers, 1994). The basal coal seams can be quite thick and extensive, and in places, up to five coal-bearing intervals are stacked on top of each other. Collectively, there can be at least twelve individual seams within those five intervals. Regionally, the Fruitland Formation is confined between relatively impermeable strata above and below, and large-scale faulting has not fragmented the basin. As discussed in more detail below, the hydraulic conditions of the stratigraphic system enhance pressure within the system. Thermal maturation of the coals has been ideal for methanogenesis, particularly in the northern part of the basin that extends into Colorado. The regional cleat systems that provide the primary control on porosity and permeability in the coals are enhanced by regional and local structural trends. The primary characteristics leading to favorable CBM production (from Kaiser and Ayers, 1994) are summarized below:

- **Coalbed thickness.** Thicker coal seams hold more gas and produce more gas because they can be more effectively de-pressured. In the San Juan Basin the thickest coal seams are found southwest of the pinch-outs of the Upper Pictured Cliffs sandstone tongues and northeast of the structural hingeline. The belt of thickest coal seams trends to the northwest, roughly parallel to the Western Interior Seaway shoreline.

- **Coal rank.** Coal requires thermal maturation in order to generate methane, referred to as "entering the thermogenic gas-generation window". Driven by depth of burial and thermal history, the higher rank coals are found at the northern end of the basin.

- **Pressure.** Greater pressure can sometimes equate to higher gas volume. The northern part of the San Juan Basin is characterized as over-pressured with the transitional boundary to under-pressured conditions following the structural hingeline. The causes of the high reservoir pressures are thought to be 1) stratigraphic changes that reduce permeability to the southwest, 2) local faulting along the structural hingeline that offsets individual coal seams, and 3) regional groundwater flow patterns that transport groundwater from the recharge areas at the outcrop into the basin interior through a well confined stratigraphic interval.

- **Structure.** Fracturing is the primary control on permeability in the Fruitland Formation and is manifested as the regional cleat systems in the coals, formed during coalification, and as local tectonic fractures. Although large-scale regional faulting has not been identified in the basin, local faulting and folding, often not identified on regional geologic maps, may play a major role in enhancing permeability and trapping methane. Many of the structural features are related, and/or are enhanced, along the structural hingeline.

4.0   COALBED METHANE PRODUCTION

Through 2004, the San Juan Basin has produced more CBM than any basin in North America. Within the basin in Colorado, a significant portion of the 4.2 Tcf total CBM gas production in the state has come from the high productivity region known as the Fairway, which stretches roughly from the northwest edge of the basin just north of the Colorado-New Mexico state line east-southeastward into New Mexico (Figure 4.1). The annual gas production history for the Colorado portion of the basin is summarized on Figure 4.2.

4.1   Northern San Juan Basin CBM Gas and Water Production History

Over most of the San Juan Basin, the production of methane from CBM wells is accompanied by the production of water. Because of the complications of producing methane from the low permeability Fruitland Formation coals encountered in the San Juan Basin, most, if not all, wells are stimulated to enhance production. In the usual situation, after a well is completed and stimulated, the primary production is water. Often no gas is produced initially. As water is produced and formation pressure at the well is reduced, gas production increases and water production declines (Figure 1.2). In a few areas of the basin, gas production, with very little or no water production occurs from the onset. This is uncommon overall, and where it occurs, it is primarily in New Mexico.

In addition to summarizing CBM gas production, Figure 4.2 also shows total annual water production from CBM wells in Colorado for the period 1985 through 2004. As can be seen, annual CBM water production increased rapidly in the first eight years following initial CBM production, peaking at nearly 34 million barrels (slightly more than 4,300 acre-feet[1]) in 1993. Water production rates declined to approximately 23 million barrels (3,000 acre-feet) by 1998 and have remained relatively constant since then. Similar to the normal production curve for a single CBM well, total annual CBM gas production increased more slowly than water production.   Gas production, however, continued to increase beyond 1993 when water production peaked, and 2003 and 2004 were the years of highest gas production in the basin.

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[1] An acre-foot is the amount of water that is required to cover an area of one acre (about the area of a football field) with one foot of water. One acre-foot equals 43,560 cu. ft. or approximately 326,000 gallons of water. For comparison purposes, the 3,000 acre-feet of water which were produced from about 1,500 CBM wells in the northern San Juan Basin in 2004 is similar to what would be produced from six irrigation wells, each pumping at a rate of slightly over 600 gallons/minute, during a six-month irrigation season.

Projections for gas production in 2005, based on the first seven months of the year, indicate that 2005 could be even more productive than 2003 and 2004 with more than 450 billion cubic feet (Bcf) of gas being produced for the first time in the basin in Colorado.

The areal distribution of CBM gas and produced water in the San Juan Basin in Colorado are illustrated in Figures 4.3 and 4.4, respectively[2]. As shown in Figure 4.3, the majority of the gas production has been within the Fairway region in the southwestern part of the Colorado portion of the basin. In contrast, the majority of the water production has been mostly outside the Fairway and spread across the northern edge of the basin predominantly within 6 to 8 miles of the Fruitland Formation outcrop (Figure 4.4).

4.2 Well Densities and Distribution

In the Colorado portion of the San Juan Basin, initial CBM development was on 320-acre well spacing. Development began primarily in the Fairway area and has spread through the SUIT Reservation and to the north end of the basin. In 2000, for areas outside of the Fairway, a change in spacing to 160 acres was approved (COGCC, Orders 112-156 and 112-157). More recently in fall 2005, COGCC approved 80-acre spacing for certain areas within the exterior boundaries of SUIT lands (COGCC, Order 112-180) and will consider an additional down-spacing request in early 2006 (Docket # 0510-AW-18). COGCC personnel anticipate additional down-spacing requests.

Finally, for portions of the basin outside of the SUIT Reservation, the U. S. Bureau of Land Management (BLM) is developing an Environmental Impact Statement that will be used as a guide for appropriate development on federal land north of the SUIT line. In the Draft EIS (BLM, 2004) several alternatives are presented for well locations. Generally, the Draft EIS assumes that 160-acre spacing orders will not be changed. However, several alternatives include the installation of a significant number of horizontal wells and the installation of multiple wells from a single drilling pad to reduce surface disturbance in the basin.

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[2] These figures depict relative gas and water production without regard to well completion date, production duration or other variables.

4.3   Production Trends and Projections

The trend of future production of CBM gas and water in the San Juan Basin in Colorado is based not only on the previous production history and the maturity of production in the basin, but also on the complex intermixing of socio-economic factors that affect the development of all energy resources. The rapid rise in the price of natural gas in the past few years has spurred the development of production in the San Juan Basin. This, combined with the relatively clean burning characteristics of methane gas, suggests that development of CBM in the San Juan Basin will continue to occur at a brisk pace for the foreseeable future.

On the basis of CBM production in the San Juan Basin in Colorado through 2004, it appears that the Colorado portion of the basin may be nearing a maximum annual rate of gas production. The change in well spacing combined with the high market prices for natural gas may drive additional infill drilling in certain portions of the basin at a relatively high rate, resulting in potentially drawing out the period of maximum gas production for a few more years. Nonetheless, development of CBM resources in the basin is at a mature stage, and while small annual increases in the amount of CBM gas produced from the Fruitland Formation coals may occur, it is unlikely that there will be a significant and/or long-term increase in the annual rate of gas production in the basin.

Current CBM production in the basin has occurred almost entirely in La Plata County except in the far southwest corner of Archuleta County. Development of the area east of La Plata County is not certain and will depend on natural gas prices and on productivity in that portion of the basin where the coals are generally thinner, have less cumulative thickness, and are not as thermally mature as those further west and south. Scenarios for future development of CBM in the basin generally include the installation of additional wells is this area to fill out spacing allowances; however, the degree to which CBM development will progress is unknown.

5.0 HYDROGEOLOGIC CONDITIONS

5.1 Northern San Juan Basin Regional Groundwater Flow Systems

Several aquifers exist within the northern San Juan Basin, the most significant of which are the Quaternary alluvial aquifers associated with the Animas, Florida, and Los Pinos Rivers and the predominantly sandstone bedrock aquifers of the Tertiary Animas Formation, Cretaceous Mesaverde Group and Dakota Sandstone, and the Jurassic Morrison Formation (Topper et al., 2003). Within the region defined by the Hogback Monocline only the Quaternary alluvium and the Animas Formation are used for beneficial purposes; primarily irrigation, stock watering, and domestic water supply. Minor use of groundwater from the Fruitland Formation and the Kirtland Shale occurs at locations along the hogback.

With current and anticipated future CBM development limited to the Fruitland Formation, discussion of the regional groundwater flow systems in the northern San Juan Basin will focus on the Fruitland Formation and Pictured Cliffs Sandstone aquifer system (hereafter referred to as the Fruitland-Pictured Cliffs aquifer). The two formations are discussed together due to the manner in which they intertongue and the probability that fracturing may further interconnect the two hydrologically.

5.2 Fruitland-Pictured Cliffs Aquifer System Conceptual Models

Two conceptual models describing regional groundwater flow in the Fruitland-Pictured Cliffs aquifer have been described in the literature. The models are distinguished by their viewpoint concerning hydraulic communication and degree of flow-through within the regional system. Examination of the hydraulic characteristics of the aquifer and consideration of recharge-discharge volumes suggest that the models do not represent substantially different flow dynamics. Both conceptual models are presented below and discussed relative to their applicability in evaluating surface water depletion due to CBM development in the basin.

5.2.1 Continuous Through-Flowing Aquifer Conceptual Model

This conceptual model maintains that in the northern part of the San Juan Basin the Fruitland Formation and the upper Pictured Cliffs Sandstone tongues, behave as a single, through-flowing hydrologic unit (Kaiser et al., 1994). Primary evidence in support of this

interpretation includes: 1) stratigraphic relationships that place more permeable, laterally extensive coal seams between underlying less permeable sandstones and shales (main body of the Pictured Cliffs) and an overlying shale-dominant unit (Kirtland Shale); 2) hydraulic head distribution within the aquifer system showing a relatively smoothly changing pressure gradient from the outcrop southward into the basin; and 3) groundwater chemistry relationships that suggest recharge of meteoric water from the higher elevation outcrop southward into the basin. The principal elements of this model are listed below.

5.2.1.1   Recharge

The Hogback Monocline, which exposes Fruitland and Pictured Cliffs strata at elevations rising above the basin, catches Pacific moisture brought in from the west and southwest. The massive upper Pictured Cliffs sand bodies are resistant to erosion and form prominent dip slopes. Because of the sandstone's low permeability, precipitation runs off of it and flows down to the topographically lower, less resistant, and more permeable Fruitland Formation coal seams providing direct recharge of meteoric water to the aquifer.

Weathering and the release of overburden pressure as the overlying strata have been eroded away over that last 30 to 35 million years may contribute measurably to the potential for recharge to occur at the outcrop. Further, the release of overburden pressure may increase the ease of flow for a limited distance into the basin away from the outcrop.

5.2.1.2   Groundwater Flow Pathways

The most permeable layers within the Fruitland-Pictured Cliffs aquifer are the coal seams (Ayers and Zellers, 1994). Porosity and permeability are greatest within the cleats of the coal seams. Furthermore, because the sediments that typically bound the coal seams are either overbank mudstones or fine-grained well-cemented sandstones with very little primary porosity or permeability, the coal seam cleats are believed to comprise the bulk of the porosity and permeability for the Fruitland Formation as a whole (Kaiser et al., 1994). Face cleat set orientations have been compiled by Tremain et al. (1994) and are included in Figure 3.6, which shows that most face cleat orientations trend north-northwest. While it may seem that the face cleat orientation may impose a preferred orientation for groundwater flow and thus an

anisotropic permeability distribution, the very close spacing of both face cleats and butt cleats may create a relatively isotropic hydrologic media.

In addition to the coal seam permeability, fractures in the shales and sandstones that are adjacent to the coal seams are believed to provide local pathways for groundwater flow between the Pictured Cliffs Sandstone and the Fruitland Formation coal seams and may contribute to elevated water yields from some CBM wells (Questa, 2000).

AHA (2000) evaluated the effect of shingled architecture of the Fruitland coal seams on groundwater flow using a two-dimensional numerical model and concluded that the large surface area of the shale intervals separating the shingled coal seams counteracts the relative low permeability of those separating layers. While AHA assumed shale in this modeling exercise, measured sections (Wray, 2000) indicate that these layers include abundant sandstone and siltstone suggesting that actual flow through the separating layers may be higher than predicted. The shingled architecture of the basal coals, therefore, should not preclude lateral groundwater flow through the system.

5.2.1.3   Aquifer Geometry

As proposed by Kaiser et al. (1988), the Fruitland-Pictured Cliffs aquifer system in the northern part of the San Juan Basin consists of relatively permeable Fruitland Formation coal seams and upper Pictured Cliffs sandstone tongues confined between much less permeable shales and sandstones. Figure 5.1 is a north-to-south cross-section (with significant vertical exaggeration) from Kaiser et al. (1994) that shows how this package of genetically related sediments dips from the outcrop recharge area south into the San Juan Basin where depths of the confined system reach 4,000 feet below the surface in the deepest part of the basin in northern New Mexico. The thickness of the aquifer is closely approximated by the thickness of the coal beds in the Fruitland Formation.

The potentiometric surface of the Fruitland-Pictured Cliffs aquifer (Figure 5.2), as derived by Kaiser et al. (1994) using hydraulic head values calculated from over 300 well-head shut-in pressures, drill stem tests, and bottom hole pressures, suggests that recharge from the highlands along the Hogback Monocline flows downward into the interior center where artesian conditions exist. This behavior is consistent with a classical confined aquifer system.

The most significant boundary within the Fruitland-Pictured Cliffs aquifer system is inferred by an overall decrease in transmissivity to the southwest in the vicinity of the structural hingeline of the basin. This hingeline is located within the New Mexico portion of the San Juan Basin. On Figure 5.1, the structural hingeline lies between wells 7 and 2-B, very close to where the potentiometric surface begins to dip steeply to the south. The net coal thickness decreases and the thicknesses of individual coal beds decrease as many coal seams pinch out to the southwest across the hingeline. It is also postulated that local faulting along pre-existing zones of weakness may offset the more permeable layers further limiting groundwater flow to the southwest. As a result, the potentiometric surface gradient flattens up-gradient of this transition zone in an area where the aquifer is over-pressured, and steepens southward beyond the transition zone to the large under-pressured southern portion of the basin. The pressure gradients near the hingeline also indicate upward cross-formational flow in this area and further south.

5.2.1.4   Groundwater Flow

Because of the sealing nature of the non-coal strata in the Fruitland Formation and the low permeability Kirtland Shale, the Fruitland-Pictured Cliffs aquifer transitions from an unconfined water table aquifer to a confined aquifer very rapidly in a basinward direction from its outcrop. As suggested by Figure 5.2, a significant component of flow along the Fruitland-Pictured Cliffs outcrop is directed from higher elevations toward the major streams and discharges to surface water. This flow pattern of the Fruitland-Pictured Cliffs aquifer discharge to the stream systems (Figure 5.3) was simulated in the 3M project modeling efforts (AHA, 2000; Questa, 2000; Cox et al., 2001). As illustrated on Figure 5.3, this component of the regional flow system is present across a broad area of the outcrop; only at locations central to stream intersects with the outcrop, does groundwater clearly appear to flow down-dip towards the interior of the basin where artesian conditions exist.

Figure 4.4 illustrates the cumulative, relative magnitude of water production from CBM wells in the San Juan Basin in Colorado through 2004. The distribution of wells producing the most water indicates that the greatest amount of water production is concentrated in the northern part of the basin close to the outcrop recharge areas. Nearly all of the wells producing the most water lie within 9 miles of the outcrop. Enhanced permeabilities in the Fruitland-Pictured Cliffs aquifer along the northern edge of the San Juan Basin may be associated with greater fracture

density, as suggested by association of zones with enhanced water production with some of the structural features discussed in Chapter 4.

5.2.2   Compartmentalized Aquifer Conceptual Model

A second conceptual model for the Fruitland-Pictured Cliff aquifer postulates that the aquifer is highly compartmentalized, with much of it being disconnected from the outcrop. While this model shares several of the characteristics described above for the through-flowing aquifer conceptual model, the compartmentalized aquifer conceptual model, as outlined by Riese et al. (2005), differs in the following ways: 1) there is believed to be a lack of continuity of the individual coal seams and discontinuities of flow between them, 2) the major element and isotopic composition of the waters associated with CBM is interpreted to preclude regional hydraulic continuity in the aquifer; and 3) the chemical and isotopic composition of the methane likewise are interpreted to preclude such continuity.   Additional evidence of this compartmentalization includes the presence of CBM gas at virgin, or near virgin, reservoir pressures at infill well locations.

5.2.3   Summary Discussion of the Regional Groundwater System

While the continuous through-flowing and the compartmentalized conceptual models differ in certain ways, the differences primarily are a matter of degree and can be handled practically by the assignment of appropriate parameters. For example, the presence of low permeability and spatially preferential recharge flowpaths are compatible with the flow-through conceptual model—such a "flow-through" system would simply have a more restricted flow dynamic than would another system with greater permeability.

For this study, an initial hypothesis regarding the conceptual model was adopted that includes the following features:

- Recharge flows from the outcrop areas to adjacent streams and to the basin aquifer;

- Flow in the basin aquifer is primarily through the Fruitland-Pictured Cliffs aquifer;

- Flow is severely restricted within the Fruitland-Pictured Cliffs aquifer as a result of the very low permeability of these strata, even within the coal seams;

- Flow within overlying or underlying formations is even further restricted, with virtually impermeable adjacent formations; and,

- Despite the very low permeabilities and local separations between coal seams comprising flow paths, in the aggregate, there is hydraulic communication within the Fruitland-Pictured Cliffs aquifer and between this aquifer and the streams where they traverse the outcrop areas.

This hypothesis was tested in modeling efforts conducted as part of this study[3]. Modeling techniques that are premised on the existence of such conditions, despite the very low permeabilities and restricted flow pathways, were applied to the historical production data and comparisons to known pressures were made. This exercise, described further in later sections, showed that the water production data are generally consistent with this hypothesized conceptual model.

5.3 Fruitland-Pictured Cliffs Aquifer Characteristics

5.3.1 Aquifer Extent

The Fruitland-Pictured Cliffs aquifer in Colorado extends from the outcrop of the Fruitland Formation and Pictured Cliffs Sandstone at the Hogback Monocline southward into New Mexico. The maximum elevation of the aquifer occurs approximately 10 miles east of Durango, where the formations crop out at an elevation of approximately 9,000 feet above mean sea level at Vosburg Pike. Along much of its outcrop reach in Colorado, Fruitland-Pictured Cliffs strata dip relatively steeply southward (at angles between 20 and 50 degrees) towards the central portion of the San Juan Basin. Within a few miles dips flatten considerably and the Fruitland Formation dips gently to a minimum elevation of approximately 4,000 ft above mean sea level in northern New Mexico.

5.3.2 Permeability

5.3.2.1 Range of Permeability Estimates from Previous Investigations

The permeability of the Fruitland Formation coals has been extensively evaluated by CBM producers in the basin as part of exploration and production activities. However, because of the nature of the tests, they tend to provide local information with relevance to production and

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[3] The 3M modeling studies were premised on these same assumptions.

may not reflect regional hydraulic properties[4]. These values were reviewed in earlier studies (AHA, 2000; Questa, 2000) and were considered, along with other data, in calibrating flow and reservoir models of Fruitland Formation coals. The distribution of permeability used in these models (AHA, 2000; Questa, 2000) ranges from less than 1 millidarcy (md) in the central portion of the basin near the New Mexico border to greater than 100 md in some areas of the Fairway and close to the outcrop (Figure 5.4). A review of shut-in test results provided to COGCC between 2001 and 2005 reported permeabilities that ranged from 0.11 to 112 md, with most values (66 of 75) falling below 10 md.

In the northern San Juan Basin, a region of intermediate permeability is suggested by potentiometric surface maps for the Fruitland Formation that show moderately decreasing pressures south away from the outcrop towards the structural hingeline in the basin (Figure 5.2). This intermediate range is reflected in the distribution of Fruitland Formation permeabilities arrived at in the 3M modeling study, where much of the central area of the San Juan Basin in Colorado is characterized by permeabilities between approximately 1 and 30 md (Figure 5.4).

The permeability of the Fruitland Formation non-coal strata is considered to be very low (Kaiser et al., 1994; Cox et al., 2001). Due to this difference and to the fact that the non-coal bearing strata are usually not perforated, the permeability of the Fruitland-Pictured Cliffs aquifer outside of the coal seams is not considered significant for analytical purposes in this study.

5.3.2.2 Permeability Estimates Derived in this Study for Depletion Analysis

As part of this study, an analysis was made using historical production and pressure data to independently derive a spatially-averaged value reflecting regional permeability, as opposed to localized permeability. Specifically, this analysis derived an average value for transmissivity (a property reflecting permeability over the active flow interval) that would be appropriate for use

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[4] There are many complications with estimating permeabilities for coals in CBM producing regions. In the San Juan Basin, wells are stimulated after completion to improve permeability in the region of the well so that gas production is enhanced. These improvements are local effects and do not increase overall permeability of the formation; however in pressure testing these improvements must be separated from native production characteristics if formation permeability is to be determined. Additionally, two forces act in opposite ways on permeability over time in the vicinity of CBM wells. First, as water production reduces pressure in the coals, the cleats tend to be closed off by the higher effective stresses on the coals. To various extents, this tendency is negated by the increase in porosity and permeability that occurs as methane desorbs from the coal itself as the pressure drops.

in the Glover depletion analysis. By deriving this parameter value with a model employing the same conceptual hydrogeologic assumptions as are inherent in the Glover analysis, and by using long-term production and aquifer response data to derive the value, this process will incorporate much of the local variability into the calculated parameter value. This analysis, described in Appendix B, resulted in a transmissivity of 1.2 ft^2/day for the northern portion of the San Juan Basin. If a range of net coal thickness (herein considered to be equivalent to the saturated thickness of the aquifer) of 20 to 100 feet is assumed, hydraulic conductivity falls in the range of 0.012 to 0.06 ft/day, which is equivalent to a permeability of 4.4 to 21 md. This range lies within that identified in the previous 3M model investigation, but provides a parameter value that is specifically tailored to the simplified hydrogeologic assumptions inherent in the methodology identified for the depletion analysis.

As described in Appendix B, the analysis involved simulation of over 15 years of production history (COGCC electronic database, 1999 to mid-2005, and the 3M database, 1985 through 1998) from over 1,600 wells, and evaluation of long-term pressure response at 15 spatially distributed monitoring wells and four Ute production wells (Table 5.1). The analysis was conducted using the Theis analytical solution (1941) implemented with a computer program (Steven P. Larson, S. S. Papadopulos & Associates, Inc., undated). This analysis uses the monthly production rates for each production well to calculate pressure impacts over time at each monitoring well location, and superimposes cumulative pressure impacts both spatially and through time. The analysis employed an automated parameter estimation procedure that used the observed pressure changes at monitoring wells to optimize the transmissivity value.

In the analysis described above, it was determined that the Fruitland-Pictured Cliffs aquifer transmissivity value derived for the northern area of the San Juan Basin provided a reasonable match to observed pressure responses at wells in the northern part of the basin; however, this same value did not provide a satisfactory match to the pressure response at Ute wells. A lower transmissivity was calculated using a restricted set of observation wells in this area. However, data indicate that gas saturation is higher and water saturation lower in this area (generally, corresponding to the region identified as the Fairway). For this reason, use of a one-phase flow model may not be suitable for modeling pressure changes in this region.

Alternatively, the production dataset available to this study may have been incomplete in this area. Further investigation is necessary to characterize the transmissivity of this region.

5.3.3   Storage Properties

Several parameters are used to describe storage properties in aquifers. These include porosity, specific storage, storativity and specific yield. Porosity is the proportion of open space in any solid media. Specific storage and storativity relate primarily to storage within confined portions of aquifers, while specific yield relates to water released by gravity drainage in unconfined aquifer zones. These parameters are discussed below as they relate to the study area.

Porosity in coals, located primarily within the coal cleats, is low. Porosity was estimated in the 3M reservoir model (Questa, 2000) over much of the central portion of the basin as less than 1 percent. Higher values were estimated for the north and northwest portions of the outcrop.

Specific storage (S_s) is the volume of water that a unit volume of a saturated confined aquifer will release from storage under a unit decline in pressure in the aquifer. Confined aquifers release water due to the compaction of the aquifer materials and expansion of the water as the pressure drops; therefore the quantity of water released is small. The total amount of water released for an aquifer of a certain thickness due to the decline in head is called storativity (S, where $S = S_s$ x thickness). Storativity relates the volume of water released to the volume of the aquifer and is a dimensionless ratio. Common values of storativity range between 5×10^{-5} and 5×10^{-3} (Freeze and Cherry, 1979).

For this study, storativity was independently estimated using the analysis described above (Section 5.3.2.2) and in Appendix B, using historical production data, historical pressure change data, and an automated parameter estimation process. This analysis resulted in a storativity of 3.1×10^{-4} for the Fruitland-Pictured Cliffs aquifer in the northern portion of the San Juan Basin. If a range of coal thickness of 20 to 100 feet is assumed, specific storage corresponding to this value falls in the range of 3.1×10^{-6} to 1.6×10^{-5} ft^{-1}. The 3M modeling studies (AHA, 2000; Questa, 2001; Cox et al., 2001) assumed 1×10^{-5} ft^{-1} for specific storage.

Specific yield (S_y) is the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline of the water table. Because water is released primarily by gravity drainage, values are several orders of magnitude higher than the storativity in a confined aquifer. Specific yield is equivalent to the effective porosity of the aquifer and it differs from the total porosity of the aquifer by the amount of water that is held in the pore spaces after the decline in the water table.

The specific yield in the outcrop areas of the Fruitland-Pictured Cliffs aquifer is expected to exceed the porosity of the Fruitland Formation and the Pictured Cliffs Sandstone in the deeper areas of the basin. Several factors likely contribute to this: 1) the release of overburden pressure as the aquifer has eroded away allowing cleats in the coal and pre-existing fractures in the adjacent non-coal strata to expand; 2) new fractures that form due to the release of overburden pressure; and 3) enhanced porosity due to weathering of both the coals and the non-coal strata at the surface in shallow subsurface. Typical ranges for specific yield are approximately 0.01 to 0.3 (Freeze and Cherry, 1979); this value, at the least, is expected to be on the order of a few percent in the outcrop area.

The storage properties of the aquifer in the unconfined, outcrop area, are at least 100 times larger than the storage properties in the confined portion of the aquifer. This contrast in the storage properties between the unconfined outcrop area and the confined basin area is central to the conceptualization of the depletion analysis, and supports the idealization of the outcrop as a "constant-head boundary" for the confined aquifer, as will be discussed further in Chapter 6. A second implication of the large contrast in storage between the confined and unconfined aquifer areas is that the unconfined area yields significantly larger amounts of water for a given pressure decline than does the confined area. For this reason, water level declines in the outcrop area of the aquifer will be very small, essentially, dampened due to the contrast in storage.

5.3.4   Stream-Aquifer Contact, Recharge and Discharge Areas

The four primary streams that flow across the Fruitland-Pictured Cliff aquifer outcrop southward into the San Juan Basin in CBM producing areas in Colorado are, from west to east, the Animas, Florida, Los Pinos, and Piedra Rivers. There are several other streams that intersect the Fruitland-Pictured Cliffs aquifer outcrop, including, from west to east, Indian Creek, Basin

Creek, South Fork Texas Creek (which flows northward across the outcrop where it joins Los Pinos River), Beaver Creek, Skunk Creek, and Stollsteimer Creek.

The streams generally traverse saturated alluvium that lies directly above Fruitland-Pictured Cliffs strata in the riverbeds. The length of outcrop-stream contacts for the four major streams range from approximately 800 to 1,000 feet at Los Pinos River to greater than one mile at the Piedra River (Wray, 2000; BLM, 1999).

The outcrop locations are the only areas where contact between the streams and the Fruitland-Pictured Cliffs aquifer occurs in the CBM producing regions of the San Juan Basin in Colorado. Water-level measurements from one water well located on the Kirtland Shale and drilled into the Fruitland Formation indicated artesian conditions existed in the Fruitland Formation, even though the well was near the outcrop (BLM, 2004), supporting assertions that hydraulic communication between the Kirtland Shale and the Fruitland-Pictured Cliffs aquifer is not significant.

Because of the sealing nature of the strata overlying the Fruitland-Pictured Cliffs aquifer, the outcrop (along the full length of the Hogback Monocline as well as at the stream-outcrop intersections) is the only place in the northern San Juan Basin where significant recharge to and discharge from the aquifer occurs[5]. As discussed in Section 3.4.3, the geomorphology of the hogback, where the resistant Pictured Cliffs Sandstone commonly extends above the less resistant Fruitland Formation, likely facilitates recharge to the coals and weathered clastic sediments of the Fruitland Formation where they reach the ground surface or are present immediately beneath permeable, unconsolidated alluvial or colluvial deposits. Several methods of analysis have been used to estimate this recharge (Kernodle, 1996; AHA, 2000). Based on those analyses and 3M model calibration (AHA, 2000; Questa, 2000) the 3M investigators estimated recharge for the Colorado portion of the Fruitland-Pictured Cliffs aquifer at approximately 200 ac-ft/yr.

Investigators in the northern San Juan Basin have suggested that a significant portion of the hogback recharge of the Fruitland-Pictured Cliffs aquifer is returned to the surface streams in

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[5] This discounts recharge that may potentially occur at depth due to upwelling of groundwater from below the Fruitland-Pictured Cliffs aquifer through deep fracture systems (Riese et al. 2005).

the basin where they cross the outcrop (AHA, 2000; Riese et al, 2005; see also Figure 5.3). The 3M model simulated the primary streams that cross the Fruitland-Pictured Cliffs aquifer outcrop as receiving discharge water from the Fruitland-Pictured Cliffs aquifer. AHA (2000) estimated total discharge to the rivers crossing the outcrop in Colorado—which includes both the Piedra and the San Juan Rivers— as approximately 200 ac-ft/yr. Cox et al. (2001) modeled discharge as approximately 30 ac-ft/yr to the Animas River plus Basin Creek, 15 ac-ft/yr to the Florida River and 35 ac-ft/yr to Los Pinos River.

5.3.5   Spring Occurrence and Discharge

Several springs and seeps associated with the Fruitland-Pictured Cliffs aquifer have been mapped along the outcrop (Figure 5.5). While some of these seeps or springs may not actually represent discharge from the Fruitland-Pictured Cliffs aquifer (e.g., they may represent drainage from shallow surficial deposits in areas of significant relief), some of them do represent areas along the hogback where water recharged from higher elevations is able to reach the ground surface due to the artesian pressures in the aquifer. The seep and spring flows along the outcrop are not known to have been quantified; however, spring flow is typically sensitive to changes in local precipitation. Because some of the springs are used for water supply purposes by private landowners and others support wetland habitats, their continued existence is an issue in the basin. Currently, CBM producers in the basin are participating in a cooperative program with the COGCC to map and conduct water sampling from springs that occur on or near outcrops of the Fruitland Formation and Pictured Cliffs Sandstone

5.3.6   Water Level Conditions

The Fruitland-Pictured Cliffs aquifer potentiometric surface map from Kaiser et al. (1994) is shown in Figure 5.2. At this stage in the development of CBM resources (approximately 1990) in the San Juan Basin, conditions had not changed significantly from the static conditions that existed prior to CBM production.

Figure 5.6 shows the Fruitland-Pictured Cliffs aquifer potentiometric surface determined for this study for 2002-2003. The following technique was used to obtain potentiometric surface data. For most CBM wells, the COGCC database includes initial formation pressure measurements. For CBM wells completed in 2002 and 2003 these data were converted to

potentiometric surface elevations. To construct the map shown in Figure 5.7, potentiometric surface measurements from COGCC monitoring wells and surface water elevations for streams and springs located at the outcrop were included with the CBM well initial pressure measurements. While the map incorporates data collected over a two-year period, on a large scale it provides a reasonably coherent snapshot of conditions in the basin. Comparison of Figures 5.2 and 5.6 shows general agreement in form in the basin in Colorado away from the outcrop. Not surprisingly, there are several areas where pressure drops since the early 1990s have been great, the most notable being the Fairway, where pressure reductions have resulted in potentiometric surface declines that exceed 2,000 feet in some areas. In addition to this area, significant pressure declines due to CBM production can be seen east of the Animas River at the north edge of the SUIT reservation (T34NU, R8-9W; greater than 500 feet of decline), adjacent to the northeast edge of the Fairway in the central portion of the basin (T32-33N, R7-8W; 500 to 1,500 feet of decline), and south of where the Los Pinos River flows over the Fruitland-Pictured Cliffs aquifer (T34-35N, R6-7W; greater than 700 feet of decline).

Despite the declines in the potentiometric surface, there are areas of the San Juan Basin in Colorado where the potentiometric surface is still above the ground level and, outside of the Fairway, artesian conditions still dominate in the basin. Further, to date, the patterns of pressure change suggest that the Fruitland-Pictured Cliff aquifer, while generally a low permeability unit, is hydraulically connected over broad areas and that pressure trends reflect connection to the saturated unconfined aquifer at the outcrop.

5.3.7 CBM-Related Pressure Changes and Potential Stream Depletions

Areas allowing hydraulic communication between the aquifer and streams that could potentially lead to surface water depletions due to CBM water production in the Fruitland-Pictured Cliffs aquifer system include the following:

- Coal cleat systems;

- Fractures in the shales and sandstones immediately adjacent to the coal seams; and

- Vertical flow through the units overlying the Fruitland-Pictured Cliffs aquifer that are in contact with the surface streams.

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There is broad agreement that vertical flow through overlying bedrock stratigraphic units is not a factor in stream depletion in the Colorado portion of the San Juan Basin due to the extremely low vertical permeability of the overlying units. The only place where this pathway is important is the very small area at the streams themselves where the Fruitland-Pictured Cliffs aquifer is in contact with permeable, water-bearing alluvium in the stream valleys. Pressure change within the coal cleats is the primary process that would facilitate depletion of the streams in the northern part of the basin. Secondary to this would be pressure changes in fractured rocks adjacent to the coals.

5.4   Fruitland-Pictured Cliffs Aquifer Groundwater Chemistry

Several thousand water chemistry samples of Fruitland-Pictured Cliffs aquifer and near-outcrop surface waters have been collected for water chemistry analysis. This analysis includes not only major ions, but also trace element, stable isotope, radiogenic isotope and cosmogenic isotope samples. Several general observations can be made based on publications that examine Fruitland-Pictured Cliffs water chemistry.

5.4.1   Major Ion Chemistry

The most common constituents analyzed for in Fruitland-Pictured Cliffs aquifer and surface water samples are the major ion and cations. General results from the analyses of major ion sampling include the following:

- Consistent with water associated with other coal producing regions of the world, the water from the Fruitland-Pictured Cliffs aquifer tends to be sodium-bicarbonate to sodium chloride dominated. This is relatively common and likely due to the brackish near marine setting of most Cretaceous coal forming environments and to the biological processes that occur during diagenesis of organic-rich materials through the development of peat to lignite to higher rank coals.

- The ionic ratios of the CBM produced waters suggest multiple sources for the waters (Kaiser et al., 1994; Riese et al., 2005) with signatures characteristic of meteoric, near marine, and connate sources. Because of the complexity of the basin, major ions are not sufficient to determine complexities of sources of the water seen.

- Chloride concentrations suggest a meteoric water plume extends into the San Juan Basin from the northern and northwest margin of the basin. This plume shows a pronounced south-southeastward incursion from the northern boundary in an area

characterized by thick continuous coal seams where the pre-CBM potentiometric surface sloped moderately toward the south, defining an area of relatively high permeability (Kaiser et al., 1994; see also Plate 2F in Riese et al, 2005).

- Based on total dissolved solids (TDS) sample results plotted in Riese, et al. (2005; Plate 2E) concentrations of Fruitland-Pictured Cliffs aquifer waters tend to increase basinward from the outcrop toward the central basin. The northwest portion of the outcrop from between the Florida and Los Pinos Rivers to where the Fairway extends to the outcrop is characterized by brackish water with TDS values of less than 10,000 milligrams/Liter (mg/L). Beyond this area in Colorado, most of the water has TDS values that range between 10,000 and 20,000 mg/L.

- Wells with TDS values acceptable for beneficial use for irrigation or livestock watering (less than about 3,000 mg/L) occur within approximately five miles of the outcrop in the area between Los Pinos River and just south of the Animas River. Even over this area, only a few CBM wells located very close to the outcrop have TDS that are within an acceptable range for potable water supplies.

5.4.2   Isotope Chemistry

The isotope chemistry of waters produced from the Fruitland-Pictured Cliffs aquifer has been the subject of several investigations (Riese et al., 2005; Snyder et al., 2003; AHA, 2000; Kaiser et al., 1994) and is quite likely to be the subject of more detailed future work. Isotope chemistry combined with general chemistry of the water are powerful tools for identifying possible sources of water produced from the CBM wells as well as from near-outcrop monitoring or water supply wells. Primary isotopes used in these investigations have included oxygen ($\delta^{18}O$) and deuterium (δD), chlorine ($^{36}Cl/Cl$), iodine ($^{129}I/I$), and strontium (Sr^{87}/Sr^{86}).

A very large amount of isotopic data has been collected to date as discussed by Riese et al. (2005) and Snyder et al. (2003) and a detailed evaluation of the data set is beyond the scope of this investigation. However, as pointed out by Riese et al. (2005), there appear to be at least four possible sources for the water encountered in the Fruitland-Pictured Cliffs aquifer: 1) connate water, 2) recent meteoric water, 3) fossil meteoric water dating to the Oligocene (between 40 and 35 Ma) and 4) water from deeper formations. The CGS has preliminarily reviewed these data and the conclusions arrived at by Riese et al., and agree that it appears that the waters found in the aquifer are complex and have multiple sources.

It is not surprising to find complexity in the chemical and isotopic make-up of these waters given the stratigraphic and structural setting of the aquifer. Based on potentiometric head

distribution, water production, and general chemistry it appears that the aquifer does behave as a single system, at least within several miles of the outcrop. The complex isotopic signatures from production wells, however, do suggest local compartmentalization as well as fracture controlled mixing of waters of different types.

It is also important to bear in mind the way the CBM wells are completed. Typically, CBM production wells penetrate the entire producing interval and the annular space between the casing and borehole wall is cemented. The casing is then perforated at the depths of individual coal seams that appear to be favorable for methane production based on geophysical log interpretations. Although much of the stratigraphic interval should be sealed off from the well, many stratigraphic intervals may be contributing water to the well; as such, any one water sample may represent a blend of water from several stratigraphic horizons. There are also wells in the San Juan Basin that are completed by "cavitation" where the well may be open to entire coal-bearing portion of the Fruitland Formation and the borehole is allowed to cave in such a way that the water produced represents a blend from an even larger interval. With these complexities taken into consideration, it is difficult to determine the sources of production water with certainty.

5.4.3   Fruitland-Pictured Cliffs Aquifer Groundwater Age Dating Studies

In addition to using isotopes for identifying possible sources of water, radiogenic isotopes have been used for estimating dates of the waters produced from the Fruitland-Pictured Cliffs aquifer. Applications of these types of groundwater age-dating techniques have been discussed by Riese et al. (2005), Snyder et al. (2003), Sanford and Sorek (2003), AHA (2000), and Mavor et al. (1991). Primary isotopes used for age-dating water from the Fruitland-Pictured Cliffs aquifer have been carbon (^{14}C), helium (^{4}He), chlorine (^{36}Cl/Cl); and iodine (^{129}I/I).

As with the isotopic studies used to identify possible sources of the water, radiometric age dating of the waters indicates complexity of the water within the Fruitland-Pictured Cliffs aquifer. Ages range from young (^{14}C dates of less than 34,000 years [Mavor et al., 1991]) to very old (^{4}He residence times of up to 123 million years, Sanford and Sorek, [2003]). Most of the older dates (primarily from ^{129}I/I dating), however, fall in the range of approximately 26 to 56 Ma (Riese et al., 2005). Obviously the very old dates, which are much older than the estimated

73-74 Ma age of the Fruitland coal seams, are problematic (although Riese et al. suggest that much older water may have entered the system from deeper formations). Additionally, discrepancies between ages derived by different methodologies lead to questions of whether the most significant age-dating issues have to do with the validity of the application of the dating techniques or the complexity of the aquifer system. For example, for one sample cited by Riese et al. (2005), the ^{139}I age was 57.0 Ma, but the corresponding ^{36}Cl age was only 2.4 Ma.

In either case, at this stage in the development of a conceptual model for the aquifer, there appear to be too many discrepancies in the overall body of isotope data to use it in a stand-alone manner to determine the flow characteristics of the aquifer. However the isotope data is considered, in combination with major ion water chemistry data and hydraulic data, in a qualitative sense it does support a conceptual model for an aquifer where a significant portion of the recharge water discharges at modern streams and springs and only a small percentage migrates deeper into a basin that may be partly gas charged. In this case it would not be surprising to find interior regions where isotopically very old water predominates but is mixed in varying proportions with younger (but still potentially relatively old) meteoric water. Regardless, the data do not support the existence of regionally extensive barriers that would prohibit the propagation of pressure changes within the Fruitland-Pictured Cliffs aquifer from the central portion of the San Juan Basin in Colorado to the recharge/outcrop areas.

6.0 CBM PRODUCED WATER STREAM DEPLETION ANALYSIS

A stream depletion analysis was conducted to evaluate the current and projected impacts of CBM water production on flow in streams traversing the Fruitland-Pictured Cliffs aquifer outcrop. For this analysis, the DWR directed that the study team apply a specific method, the Glover analysis, because of its ease of application and utility in administrative processes. However, the DWR also instructed the study team to evaluate the suitability of the Glover analysis for use as an administrative tool in the San Juan Basin, and potentially, in other CBM-producing regions in the state.

DWR considers groundwater to be non-tributary to surface water if the withdrawal of water by a well will not, within 100 years, deplete the flow of a natural stream at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal (C.R.S. 37-90-103(10.5) and 37-92-103(11)). In Colorado, CBM produced water, like water produced from any other type of oil or gas well, is considered a waste under COGCC Rule 907 and remains under the jurisdiction of the COGCC. However, if the produced water is applied to a *beneficial use*[6] beyond those allowed under COGCC Rule 907, it is regulated by DWR through a permitting process and water users are subject to various controls to avoid injury to vested water rights. In some cases, augmentation of depletions to streams may be required. Because of the potential for the CBM wells in the San Juan Basin in Colorado to be tributary to the streams that cross the Fruitland-Pictured Cliffs aquifer outcrop and because some streams in La Plata County are already fully- or over-appropriated, the DWR is interested in a first order identification of the area within which pumping may result in stream depletion exceeding 0.1 percent of the pumped quantity within 100 years of pumping.

6.1 Previous Studies

In 2000, as part of the 3M study, two numerical models—a MODFLOW model for the San Juan Basin, and a reservoir model for the Colorado portion of the basin—were constructed (AHA, 2000; Questa, 2000). The models were developed and run concurrently and the output included assessments of the rates and locations of gas seepage that could be expected to occur in the future along the Fruitland Formation outcrop and the expected future changes in Fruitland-

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[6] "Beneficial use" means those uses for water that have been recognized as beneficial by DWR (e.g., domestic or municipal water supply, irrigation, minimum stream flow, etc.)

Pictured Cliffs aquifer pressures/water levels with CBM development. In a follow up study directed at estimating depletion from the Animas, Florida, and Los Pinos Rivers, three sub-area models utilizing previous model parameters and added model layers were constructed (Cox et al., 2001). These models simulated pre-CBM development discharge from the Fruitland-Pictured Cliffs aquifer into the three streams (and their most significant tributaries) as approximately145 ac-ft/yr. Cox et al. (2001) further calculated that the depletion to the three streams due to CBM water production in 2005 would be up to 95 to 100 ac-ft/yr, although the analysis was spatially restricted and did not include the entire CBM production area. The analysis was extended to project depletions increasing to approximately 130 ac-ft/yr by 2050, the last year simulated in the models. Data did not permit a fourth model to be constructed to evaluate depletion from the Piedra River and Stollsteimer Creek, but projection of results from the area west were used to provide an estimate of 15 to 60 ac-ft/yr of depletion from the Piedra-Stollsteimer system by 2050.

These depletion estimates are relatively low compared to flows in the rivers. The combined base flows for the Animas, Florida and Pine Rivers average nearly 200,000 ac-ft/yr (Cox et al., 2001). However, the estimated depletions for both 2005 and 2050, which rise from approximately 3 percent to 6 percent as a proportion of the current CBM water production rate of 3,000 ac-ft/yr, provide a basis for DWR's desire to conduct a stream depletion study applied to the entire CBM production area in the San Juan Basin of Colorado.

6.2   Glover Depletion Analysis

DWR has stipulated for this study that the methodology applied to the depletion analyses will be the analytical "Glover" (or "Glover-Balmer") methodology (Glover and Balmer, 1954). This method is easily applied, either in a stand-alone fashion, or through several available codes such as the DWR "DEP" program (Schroeder, 1987). The Glover methodology is premised on a number of simplifying assumptions, among them, that the flow system is dominated by a single phase (i.e., water). This and other simplifying assumptions are examined in the analysis.

6.2.1   Description of Method

In 1954, Glover and Balmer developed an analytical solution for the ratio for stream depletion to total pumpage at any given time for a well pumping from an aquifer fully penetrated by a stream. The basic form of the Glover-Balmer equation (hereafter simplified to Glover) is:

$$q/Q = erfc\left(\sqrt{\frac{a^2 S}{4tT}}\right)$$

where **q/Q** is the ratio of the quantity of stream depletion to pumping rate for time **t**, **a** is the distance of the pumping well from the stream, and **T** and **S** are the aquifer transmissivity and storativity, respectively. The complementary error function, **erfc**, is a probability function that returns a proportion (between 0 and 1) for the input value $\sqrt{\frac{a^2 S}{4tT}}$. Note that **q/Q** is a ratio of rates, and therefore independent of the pumping rate.

Because of the flexibility inherent in the solution and the ease of its application, the Glover analysis has been adopted for use in administering water rights law in a number of stream-connected basins of the western United States. For example, in Colorado, C.R.S 37-92-308(3), specifies its use in the South Platte River basin in conjunction with stream depletion factors (Jenkins, 1968) that have been calculated from numerical groundwater flow models prepared for the basin.

6.2.2   Assumptions and Limitations

The Glover analysis is premised on several idealizations (or simplifying assumptions) regarding aquifer conditions and geometry. There exist few natural environments that fully satisfy idealizations such as these; however, through careful configuration and application of the model, the error associated with divergence from the ideal case can be minimized and useful information for planning and management can be obtained. The idealizations inherent in the Glover analysis and comments regarding the application of the method to the San Juan Basin are provided below:

- *The aquifer is homogeneous, isotropic, and of semi-infinite extent.* Previous studies and the results of production well transient pressure tests have indicated that permeabilities for the Fruitland Formation coals vary over a range, from areas with greater than 100 md in the Fairway and along the outcrop to a large portion

of the central portion of the basin in Colorado where permeabilities are less than 10 md. In order to effectively apply this method to the Fruitland-Pictured Cliffs aquifer in the San Juan Basin, average parameters must be identified that will approximate the aggregate behavior caused by spatially distributed parameters.

- *The boundary at which depletions are calculated is a linear stream that fully penetrates the aquifer, where the streambed is in hydraulic connection with the aquifer.* The model geometry must be set up in a manner that best approximates this assumption, given the nature of this hydrogeologic setting.

- *Flow within the aquifer is horizontal.* Due to the sealing nature of adjacent formations, vertical flow to/from overlying or underlying formations is considered negligible and flow occurs primarily within the Fruitland-Pictured Cliffs aquifer; therefore, this idealization is not considered problematic. Although the formation dips into the basin, to the south, on a regional scale, the flow can be considered horizontal within this layer without introducing significant error.

- *Flow is dominated by one phase.* This method only considers one-phase flow. Where water extraction and pressure changes dominate the flow regime, this assumption is acceptable. Where gas pressures dominate the flow regime, this method will not yield useful results.

The implementation of the Glover analysis has been structured to conform to these idealizations to the extent possible, as described in the following sections.

6.2.3 Parameter Estimation

Effective average formation parameters have been identified through parameter estimation techniques using an analytical model that employs the same simplifying assumptions as does the Glover analysis. This analysis was summarized in Chapter 5 and is more fully described in Appendix B. The advantage of this method is not only that derived parameters reflect the history of well production rates throughout the basin and observed pressure changes at numerous monitoring wells, but also that the derived parameters are consistent with the modeling methodology to be employed. In other words, parameters obtained via history-matching using an idealized model will be applied in a similar idealized model. The resulting parameters are "effective averages" that take into account both the observed data and the model idealizations with respect to geometry, homogeneity and other simplifying assumptions. Consequently, this approach should be fairly robust in terms of predicting system behavior on a broad scale.

6.2.4 Geometry and Problem Configuration

The Glover analysis assumes that a fully-penetrating, linear stream is present at some distance from a pumped well. The primary streams of interest for this analysis are those discussed above, the Animas, Florida, Los Pinos, and Piedra Rivers and tributaries that cross the Fruitland-Pictured Cliffs outcrop, as well as springs and seeps within the outcrop area. The streams traverse the outcrop and are generally oriented orthogonally to the outcrop. Therefore, they more resemble a series of small ponds in their intersection with the aquifer than they do linear streams. However, between the streams, along the outcrop, are located tributaries, seeps and springs. With unconfined conditions in the outcrop area, and given that the outcrop receives recharge that for the most part flows directly to streams, when compared to the basin aquifer, the outcrop itself is "stream-like". The outcrop is "stream-like" because it has a storage capacity that is orders of magnitude greater than that of the confined aquifer and because it forms a band of enhanced permeability between the streams supporting an active flow system to the streams. Therefore, for this analysis, the entire area of outcrop is handled as a constant-head boundary, or, "stream". Attributes supporting this assumption include:

- The outcrop forms a gently curved arcuate boundary/stream. The scale of analysis allows the outcrop to be assumed to be essentially linear.

- The outcrop is the primary source of recharge for the aquifer; therefore, it can be considered to be a pseudo-constant head boundary. This is equivalent to a stream with a constant head. Given the large unconfined storage (specific yield) for the aquifer at the outcrop and the large area of the outcrop, along with the overall magnitude of total produced water in the Colorado portion of the basin, (approximately 3,000 ac-ft/year), it is not likely that measurable drawdown in the water table surface could be induced by the pumping such that this assumption would be violated.

- Because a significant portion of the water recharging at the outcrop discharges at the streams where they cross the outcrop, any depletion assigned to the outcrop section of the "stream" due to pumping is likely to deplete the stream in turn by reducing the amount of discharge from flow lines that go directly from the outcrop to the stream.

The approximation of the outcrop as the stream provides the most realistic geometry for the solution of the Glover analysis. This configuration offers the following advantages:

- Stream depletion is not calculated from reaches traversing the inner basin area, where the stream is hydraulically separated from the Fruitland-Pictured Cliffs aquifer by many hundreds or thousands of feet of impermeable shales; and,

- Depletions to outcrop storage, springflow and seep flow are "lumped" into the calculated depletion and are not ignored in the analysis.

However, this conceptualization results in some loss of precision in timing of depletions to streams. Because the configuration considers the entire outcrop to be "stream-like", depletions calculated for the outcrop areas of the "stream" will be shifted forward in time by an amount approximately equal to the subsurface travel time from outcrop areas to the actual streams. This offset is probably on the order of months to a few years. While precision in timing involves an offset, the total calculated depletion is expected to be a fairly good approximation of the overall impact to streams, tributaries and springs in the outcrop area.

6.3   Results of Glover Stream Depletion Analysis

Using the optimized values of transmissivity and storativity obtained from the parameter estimation analysis, the Glover analysis was applied to CBM wells within the Colorado portion of the San Juan Basin to identify the area where stream depletions exceed one tenth of one percent of pumping within 100 years; and, to quantify current and future depletions at the outcrop. A detailed discussion of the Glover stream depletion analysis is provided in Appendix C.

6.3.1   Characterization of Percentage Depletions

The area where stream depletions exceed one tenth of one percent of pumping within 100 years occurs is shown on Figure 6.1 and generally includes the area within about 10 miles of the outcrop. The analysis supporting identification of this area is fairly well supported by data in the north-central portion of the basin. To the east, observation data is much less abundant. However, since the Fruitland-Pictured Cliffs aquifer in this area appears to be water saturated and to have significant regions where net coal thicknesses exceed 30 feet (Ayers et al., 1994; Riese et al., 2005), it appears reasonable to extend the analysis into this area. This analysis was not extended to the west, in the vicinity of the Fairway. As described in Chapter 5, the parameter estimation analysis suggested reduced permeability to water in that area, possibly indicating a

need for two-phase flow analysis. The likelihood of this or other potential explanations for the different behavior in that area were not resolved during this study.

6.3.2   Current Extent and Magnitude of Depletions

To estimate current magnitude of depletions, the Glover analysis was run using monthly water production rates to solve for basin-wide depletions on the Fruitland outcrop. Using this method, current depletion (as of August 2005) for all wells pumping within the basin in Colorado is 156 ac-ft/yr. This quantity does not differ greatly from the depletions calculated in the 2001 3M modeling—95 to100 ac-ft/yr for projections for 2005 for the Animas, Florida, and Los Pinos Rivers (Cox et al., 2001), particularly given that those models did not include the entire CBM production area.

6.3.3   Future Extent and Magnitude of Depletions

To evaluate future depletions, further development of CBM resources was estimated based on information provided in well spacing orders for the Fruitland Formation in the San Juan Basin (available for review on the COGCC website at http://oil-gas.state.co.us/), on the alternatives presented in the Draft EIS for the northern San Juan Basin (BLM, 2004), and on the basis of information provided by COGCC personnel. Figure 6.2 illustrates the number of future Fruitland Formation CBM wells estimated to be developed in each section in the San Juan Basin in Colorado that is within the area defined by the Fruitland-Pictured Cliffs outcrop. Two related scenarios were modeled: in the first scenario, all potential future wells were included in the analysis, for a total of 1,516 wells; in the second, wells within a 1.5 mile buffer along the outcrop were omitted. This second scenario recognizes current COGCC prohibitions on drilling within 1.5 miles of the outcrop; under it, 1,155 future wells were installed.

To determine production at times in the future, average well life and water production were estimated. Using statistics from existing and shut-in or abandoned production wells, 3M information, and data from COGCC, the period of production of water from a CBM well was assumed to be 10 years (the well is not considered to have ended its gas production life at this point, but the production of water from the well ceases) and water production rate was assumed to be 64 bbls/day. Water production for currently producing wells was also ended after 10 years, but average well production for the period between the last reported value and shut-down was set

equal to the average production rate of production for the well in 2005. Existing wells already active beyond 10 years were shut down as of September 2005. Future wells were brought on-line at a rate of 100 wells per year. This rate is based on the rate at which existing wells were installed between 2000 and 2005.

Using these assumptions, depletion curves for currently operating wells and under both buffered and unbuffered future well scenarios were determined. These curves, shown in Figure 6.3, indicate that the depletion rate for existing wells will peak in about 2020 at 164 ac-ft/yr and that by 2070 depletions will drop below 100 ac-ft/yr. Under the buffered future well scenario (i.e., no wells within 1.5 miles of the outcrop), depletions will peak in approximately 2035 at 171 ac-ft/yr, and will drop below 100 ac-ft/yr by 2150. Beyond 2150, depletions continue to slowly drop, but do not go below 50 ac-ft/yr until about 2300.

Figure 6.3 also illustrates the potential impact of allowing CBM well development within 1.5 miles of the outcrop. If wells are installed within sections lying within 1.5 miles of the outcrop, and at the densities shown in Figure 6.2, depletions will peak in about 2025 at over 500 ac-ft/yr. However, by 2150, depletions are roughly equal for both future scenarios. This results from the proximity of the wells in the buffer zone to the outcrop; pumping depletions are rapidly manifest at the outcrop, but the effect of well shut down also propagates quickly. In contrast, depletions from wells further from the outcrop are more slowly manifested. Figure 6.4 illustrates the relative timing and degree of pumping depletions on the outcrop for wells one, two and four miles distant. For wells located one mile from the outcrop, depletions peak 11 years following pumping initiation; for wells at two miles distance peak impact occurs approximately 20 years after pumping begins; and for wells four miles from the outcrop, depletions do not peak until more than 50 years after pumping begins.

7.0 NORTHERN SAN JUAN BASIN CBM WATER PRODUCTION AND REGULATORY IMPLICATIONS

Depletions to surface water streams from CBM well groundwater production have potential implications to water rights holders, the State of Colorado, and to downstream water users not in Colorado. For these reasons it is necessary to evaluate the current regulatory framework associated with the production of CBM water, the potential for beneficial uses of such water, and the interstate ramifications of the consumptive uses of such water.

7.1 Regulatory Framework

COGCC has regulatory jurisdiction over all CBM operations, including the generation, transportation, storage, and treatment or disposal of exploration and production wastes. This includes water produced during CBM operations unless that water is put to beneficial use in accordance with DWR regulations. The jurisdictional framework is illustrated in Figure 7.1. A summary of DWR authorities regarding groundwater administration and CBM water production is provided by Wolfe and Graham (2002) and is included in Appendix D of this report.

Under existing regulations, as long as CBM produced water is handled as waste under COGCC Rule 907, it remains under the jurisdiction of the COGCC. However, if CBM produced water is put to a beneficial use beyond the uses allowed under Rule 907, it is subject to DWR regulation. Furthermore, if the CBM produced water is discharged to the waters of the state, a permit must be obtained from the Colorado Water Quality Control Division (WQCD)[7]. The regulatory framework may appear complicated, but the authority and guidance to put CBM water to beneficial use are well established.

In Colorado, CBM produced water, like water produced from any other type of oil or gas well, is considered a waste. In the San Juan Basin most CBM produced water is disposed by injection into Class II UIC wells, which are regulated by COGCC on lands north of the SUIT line and by EPA south of the SUIT line.

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[7] "Waters of the state" refers to all surface and underground waters that are tributary to natural streams, except designated groundwater as specified in C.R.S. 37-90-103(6)(a) and related statutes.

7.2 **Potential Beneficial Uses of CBM Produced Water**

There are several beneficial uses for waters of the state recognized by DWR. Widely recognized uses include domestic and municipal water supply, irrigation, livestock watering, manufacturing and industry, fire protection, dust suppression, minimum stream flows, and augmentation. In the San Juan Basin, very little CBM water is used for beneficial purposes, in part because the quality of the water in the Fruitland-Pictured Cliffs aquifer in most of the Colorado portion of the basin is too poor for most uses that involve a sizeable and relatively continuous supply of water. Table 7-1, which has been constructed on the basis of existing published TDS concentration maps for Fruitland-Pictured Cliffs aquifer produced water (Kaiser et al, 1994; Riese et al., 2005), summarizes the potential for beneficial use of produced water in Colorado in the San Juan Basin[8].

As Table 7-1 suggests, there is only a small potential for CBM produced water in the basin to be put to beneficial use without the construction of treatment and/or delivery infrastructures. Because of the relatively low demand for water for local municipal and industrial supply purposes, it is unlikely that the construction of the necessary infrastructure to treat/transfer water to points of use in the San Juan Basin will be economically feasible in the near future.

7.3 **Interstate Stream Compact Ramifications**

Interstate stream compacts relating to surface waters from the San Juan Basin in Colorado (where the border of the basin is defined by the Fruitland-Pictured Cliffs outcrop) to other states include the Colorado River Compact (C.R.S. 37-61-101) and the Upper Colorado River Compact (C.R.S. 37-62-101). The La Plata River Compact (C.R.S. 37-63-101) is not relevant to CBM produced water in the San Juan Basin because the La Plata River does not occur within the basin as defined by the Fruitland-Pictured Cliffs outcrop. Deliveries to New Mexico from the La Plata River are administrated at the Colorado-New Mexico border above where the Animas River, which does occur in the San Juan Basin, joins the La Plata River.

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[8] There are several other water quality requirements which factor into determinations of whether or not water is suitable for discharge or beneficial use, but TDS provides a useful first order measure.

Article III(a) of the Colorado River Compact apportions 7.5 million ac-ft/yr of water both to the states of the "Upper Basin", of which Colorado is one, and to the states of the "Lower Basin". In accordance with the compact, surface waters that flow from the San Juan Basin in streams tributary to the Colorado River constitute a portion of the 7.5 million ac-ft/yr of water that must be delivered to the lower basin at Lee Ferry in northern Arizona, downstream of the confluence of the San Juan and Colorado Rivers. The Upper Colorado River Compact further apportions the waters of the upper basin of the Colorado River among the states of Colorado, New Mexico, Utah, and Wyoming. In accordance with Article III(a)(2) of the compact, Colorado is apportioned 51.75 percent of the water that is available for consumptive use from the Colorado River and its tributaries in the upper basin. Whether Colorado over-appropriates water under this compact depends on total consumptive use from all the streams in the upper basin in Colorado, not on consumptive use from any single stream. However, Article XIV of the compact does apply specific conditions to the consumptive use of water from the San Juan River and its tributaries. Since all the streams flowing from the San Juan Basin in Colorado are tributary to the San Juan River, stipulations in Article XIV are pertinent. Because the San Juan River (including its tributaries) is the only upper basin stream in New Mexico, Colorado is required to deliver enough water to New Mexico to allow New Mexico to make full use of its appropriation under Article III(a)(2) of the compact. Conditions for allocation of the waters of the San Juan River and its tributaries are set forth in Article XIV(a) through (e), which among other conditions specifies: (a)(1) that Colorado has a prior right to all water appropriated at the time of the signing of the compact, and (c) that both states must share proportionately in the reduction of consumptive use in times of water shortages. The Colorado Department of Natural Resources must evaluate whether current regulation of the depletions resulting from CBM produced water is appropriate in the context of the Upper Colorado River Compact.

8.0   SUMMARY OF CONCLUSIONS

For this study, information was reviewed to provide background on the hydrogeologic setting related to CBM production in the northern San Juan Basin; production and pressure data were analyzed to identify suitable aquifer parameters for a stream depletion analysis; and, stream depletion due to the production of groundwater from CBM wells was estimated.

Primary study findings include:

- *Gas and water production*: A database of monthly CBM gas and water production for all wells in the basin from 1985 to the present was compiled. Based on that database, through July 2005, more than 4.2 Tcf of gas and 400 million bbls (52,000 ac-ft) of water have been produced from CBM wells in the San Juan Basin in Colorado. The annual rate of gas production is continuing to rise and is projected to be above 450 Bcf in 2005. Annual water production peaked in 1993 at nearly 34 million bbls (4,300 ac-ft) and has been relatively steady at close to 23 million bbls (3,000 ac-ft) since.

- *Hydrogeologic setting*: CBM is produced from coals within the Fruitland Formation. The Fruitland Formation and the underlying, closely related, Pictured Cliffs Sandstone, extend to an outcrop area that is traversed by several streams. Groundwater flow occurs through coal cleats and fractures although the unit transmissivity is very low. No significant barriers between the CBM wells and the outcrop were identified that would negate an assumption of hydraulic connection from the wells to the streams at the outcrop; albeit, the propagation of depletions is limited by the low transmissivity.

- *Estimation of aquifer parameters*: Aquifer parameters broadly representative of the Fruitland-Pictured Cliffs aquifer in the northern part of the basin were developed through an automated parameter estimation procedure and simulation of water production at over 1,600 wells. The simulation employed an idealized analytical model (the Theis model, with image wells to handle the stream boundaries and superposition to handle the variable pumping schedules for each well). Best-fit parameters of 1.2 ft^2/day for transmissivity and 0.00031 for storativity were obtained. These parameters, while a good representation of average conditions in the northern part of the San Juan Basin, are not considered applicable to the Fairway region. Parameter estimation for the Fairway region will require further evaluation.

- *Stream depletion analysis*:
  - Using the Glover analysis with the average transmissivity and storativity values given above, an area within which stream depletions are calculated to exceed, within 100 years, one-tenth of one percent of the rate of water withdrawal from a well, was identified. This area generally occurs within

  approximately 10 miles basinward from the Fruitland-Pictured Cliffs aquifer outcrop.

- It was concluded that the conditions in the far western area in the San Juan Basin (the Fairway) were sufficiently different that extension of this demarcation was not applicable to that area. Further analysis is needed to assess the degree of stream depletion from the Fairway region.

- The current stream depletion in the San Juan Basin in Colorado is estimated at 156 ac-ft/yr.

- Stream depletion analysis for two related scenarios for future CBM development in the San Juan Basin in Colorado showed that the timing and extent of depletions are most sensitive to the distance from the outcrop of CBM wells. If the current 1.5-mile buffer is assumed to remain, the maximum depletion is approximately one-third of the maximum depletion that would occur if infill development up to the outcrop occurred (171 ac-ft/yr vs. greater than 500 ac-ft/yr). The differences become less apparent with time after the production of water ceases, and in both cases, depletions above 100 ac-ft/yr persist for more than 100 years after the end of water production.

- ***Suitability of the Glover method:***

  - ***Northern San Juan Basin area***: Given the complexity of the structural geology and the lenticular nature of the Fruitland Formation coal seams, use of transmissivity and storativity values obtained by calibration against measured drawdowns in the aquifer is an effective means to absorb the far field effects of the aquifer heterogeneities. With such parameters, and with the orientation of the model stream boundary such that springs, seeps and unconfined water table storage are not ignored in the assessment of stream depletion, the Glover analysis provides a useable first-order determination of depletion for most of the area within the San Juan Basin in Colorado.

  - ***Fairway area***: The methods applied were not immediately successful for the Fairway region; additional analysis would be needed to extend this work to that area. This may be a function of higher gas saturations in that area; however, other explanations have not been ruled out.

  - ***Other CBM areas in Colorado***: Several items factor into the appropriateness of the Glover analytical approach. These include:

    - The nature of the connection between the coal-bearing horizons and surface water streams and/or aquifers being used for beneficial purposes;

    - The ability to determine reasonable aquifer parameters either through the availability of credible existing aquifer parameter information (permeability, storativity) or sufficient pressure monitoring information to allow calibration of aquifer parameters;

- The conditions within the aquifer itself: Is the aquifer dominated by a single fluid phase, or, do conditions such as exist in the Fairway region of the San Juan Basin occur elsewhere? Is the coal bearing unit primarily a one-layer flow system? Are any significant hydraulic barriers or contrasts present between the CBM production area and the outcrop/stream areas?

  These points would require evaluation prior to judging the applicability of the Glover method for estimating stream depletion in other basins.

- *Regulatory framework*: When produced water is disposed as a waste, regulatory authority lies with COGCC under Rule 907. If water is beneficially used beyond those uses allowed under Rule 907, regulatory authority for use lies with the DWR; if water is discharged to waters of the state, the discharge must be permitted by the CDPHE-WQCD. The Agencies' roles in these situations are clear; even though the process of obtaining approval to put CBM produced water to beneficial use may require multiple permits.

- *Possibilities for beneficial use of CBM produced water*: Beneficial use of produced water in the San Juan Basin is limited due to:
  o the high TDS values of the water; and,
  o the lack of economic drivers to justify expensive treatment and conveyance systems from points of production to points of use.

It appears that the Glover analysis, as a first-order indicator of general conditions, can be applied successfully to a significant portion of the San Juan Basin in Colorado and that the conclusions drawn from the analysis should be useful to the DWR and COGCC in administering CBM water production in the basin in Colorado.

9.0   REFERENCES

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Figure 1.1.
San Juan Basin Regional Setting
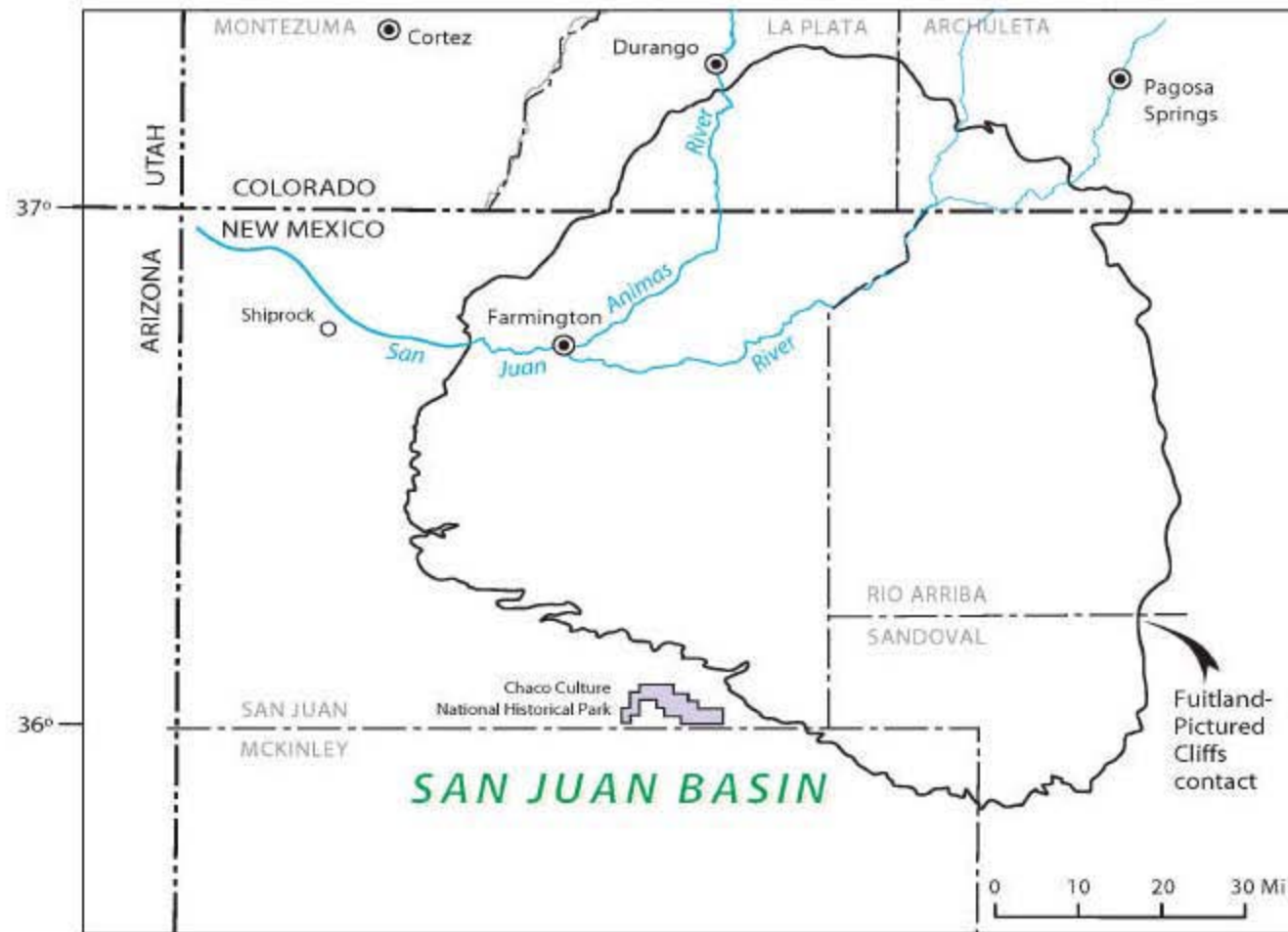
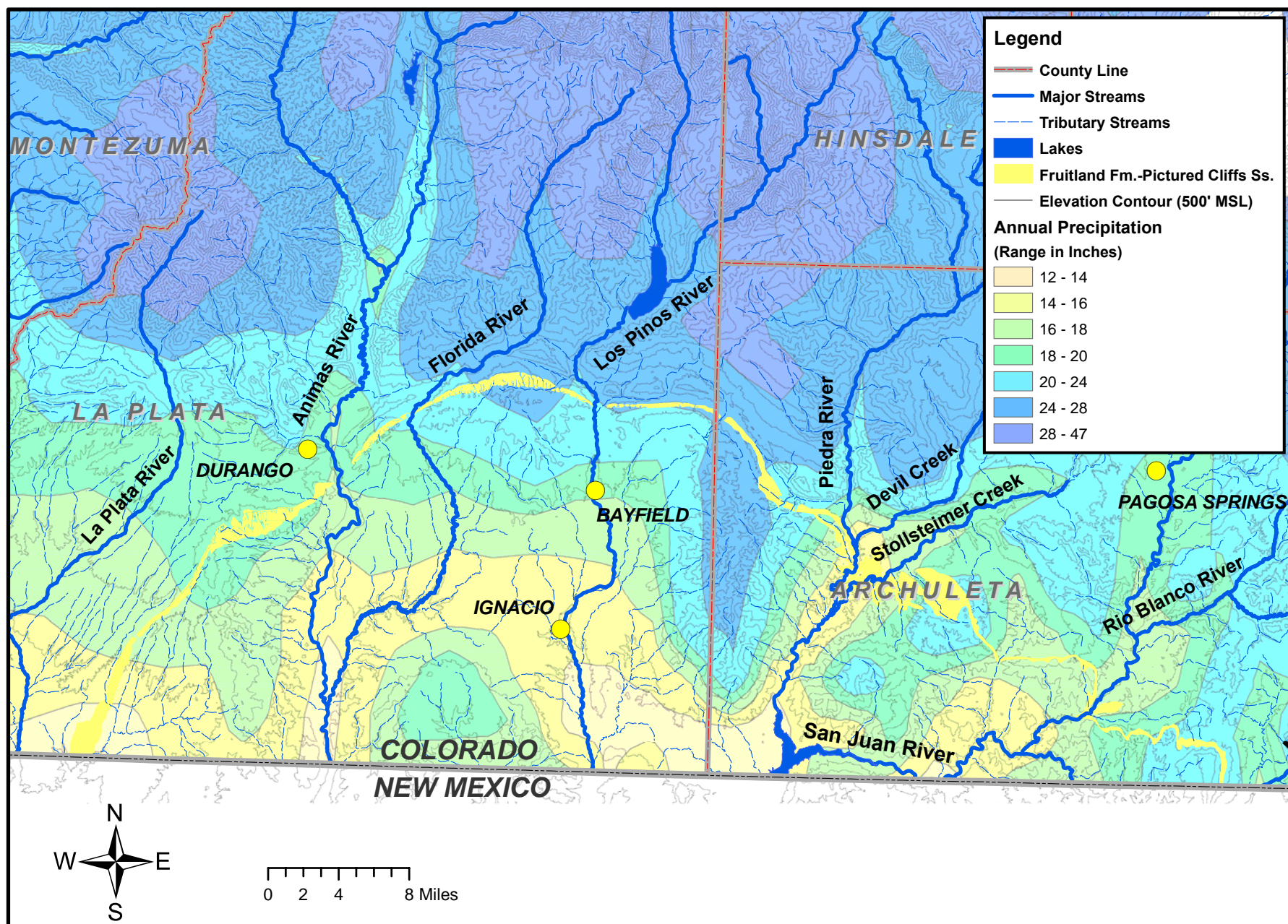**Figure 2.1. Annual Precipitation on the Fruitland Formation Outcrop, Northern San Juan Basin**

Figure 1.2.
San Juan Basin CBM Gas and Water Production Plots
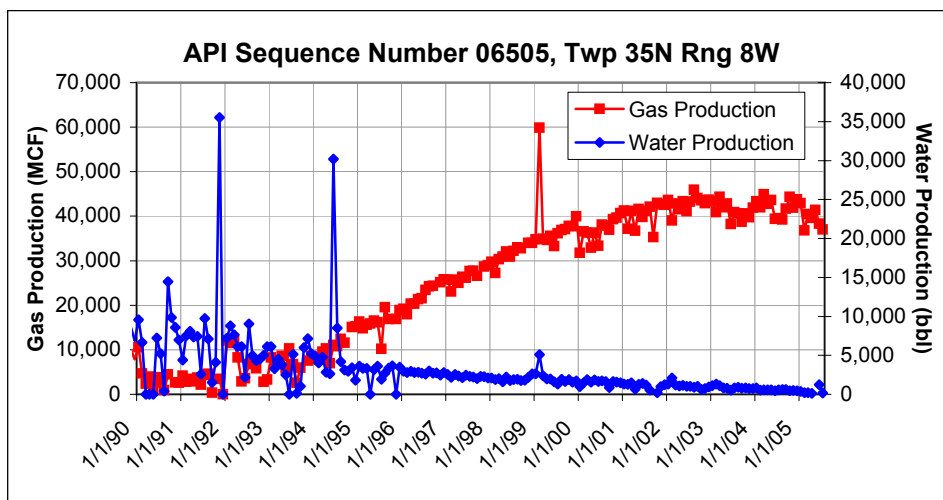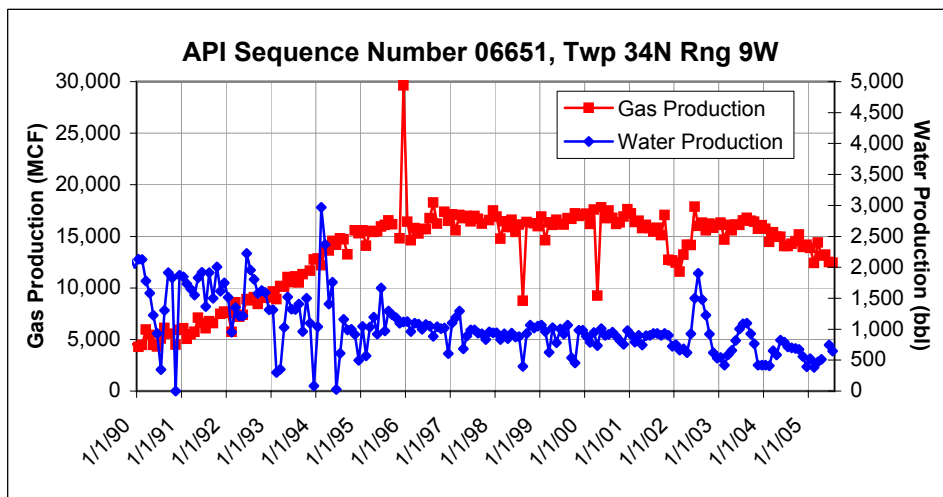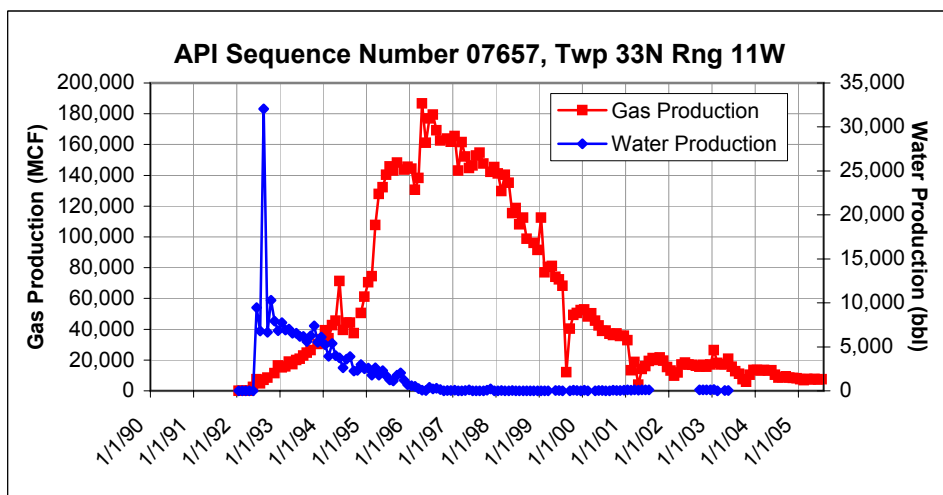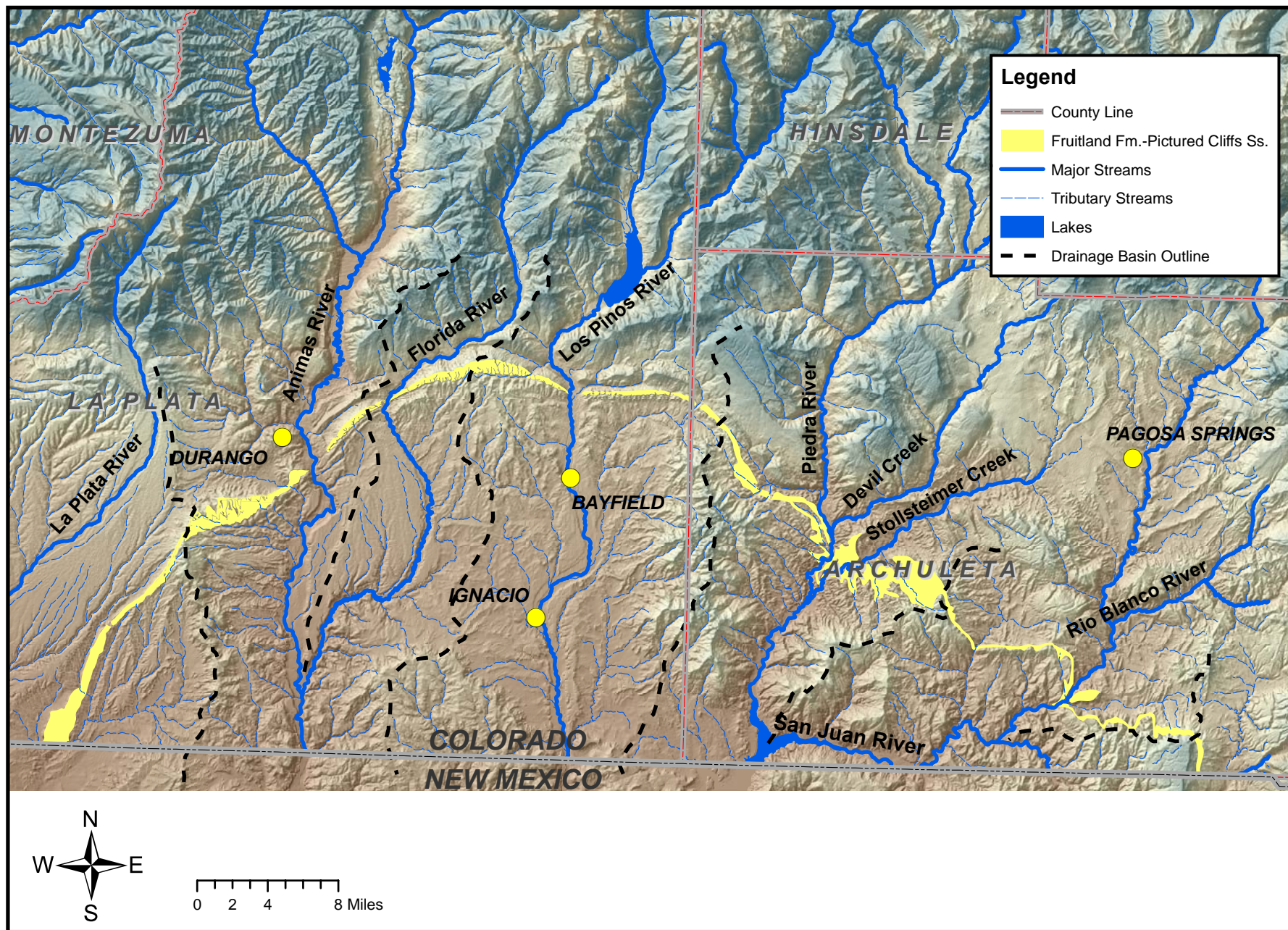
Figure 2.2. Stream Systems and Major Drainage Basins of the Northern San Jan Basins

Figure 3.1.
Late Cretaceous Western Interior Seaway

Figure 3.2.
Upper Cretaceous Time-Stratigraphic Chart, San Juan Basin
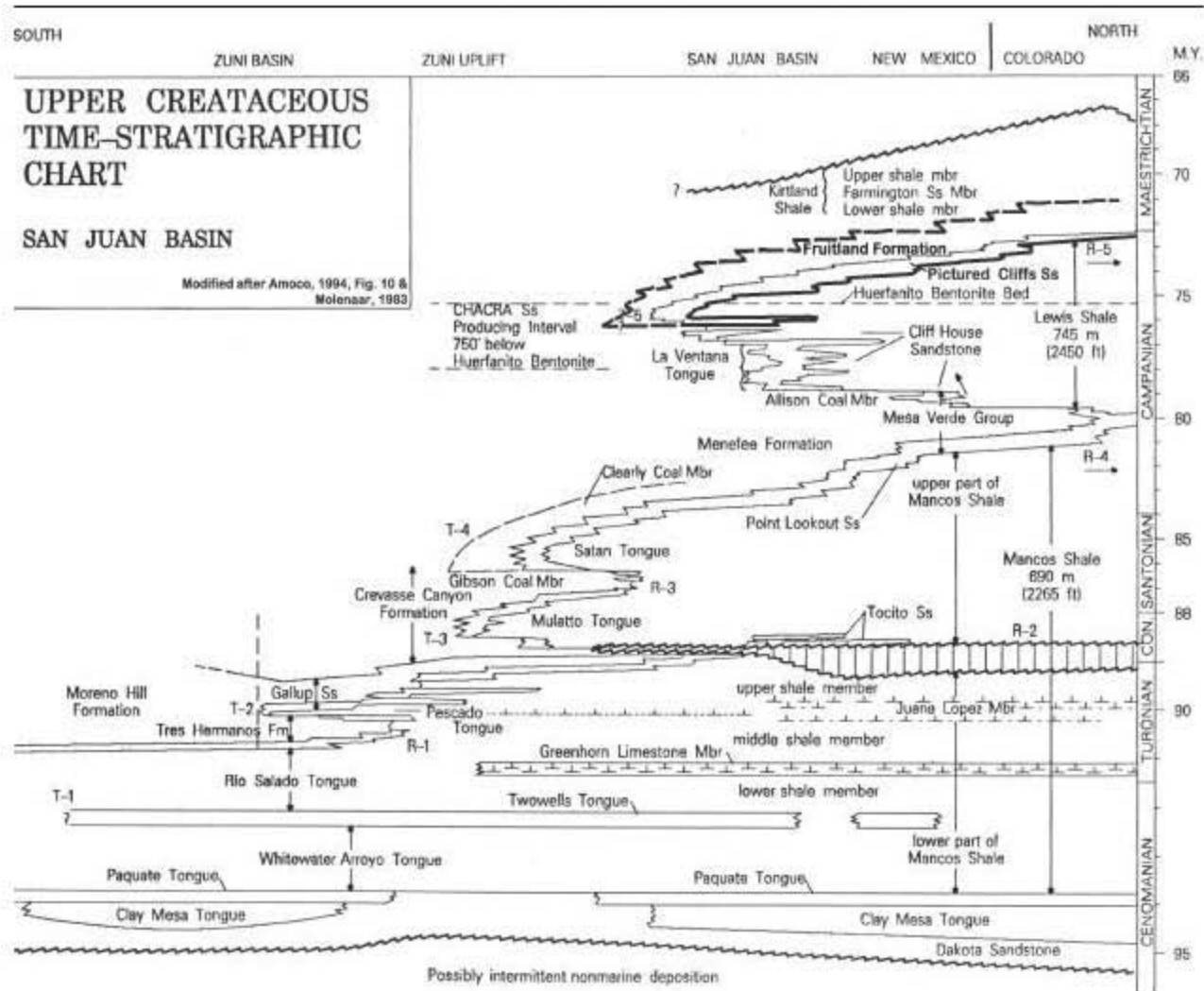
(Wray, 2000)
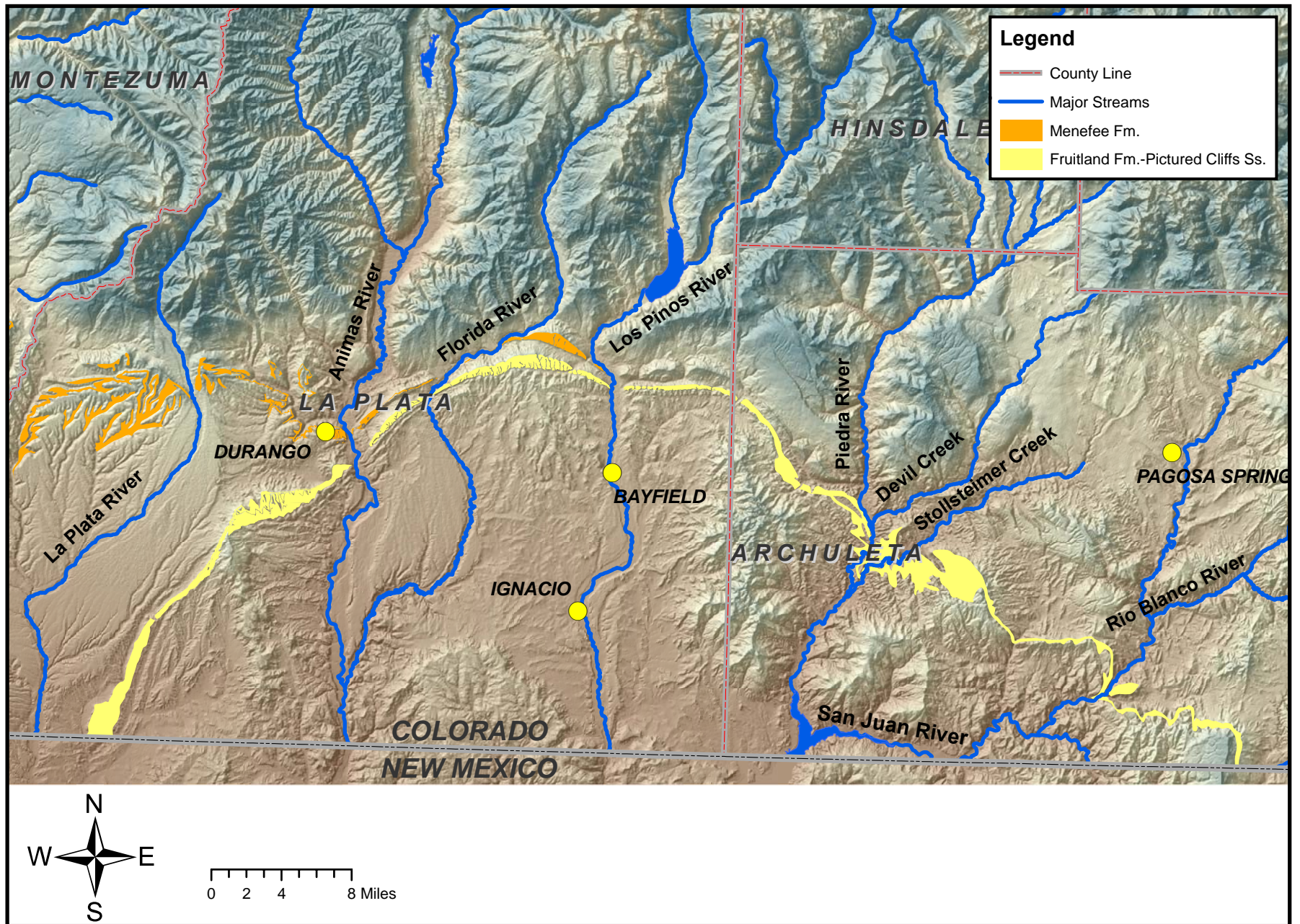
Figure 3.3. Upper Cretaceous Coal-Bearing Formations, Northern San Juan Basin

Figure 3.4.
Fruitland-Pictured Cliffs Stratigraphic Cross Section
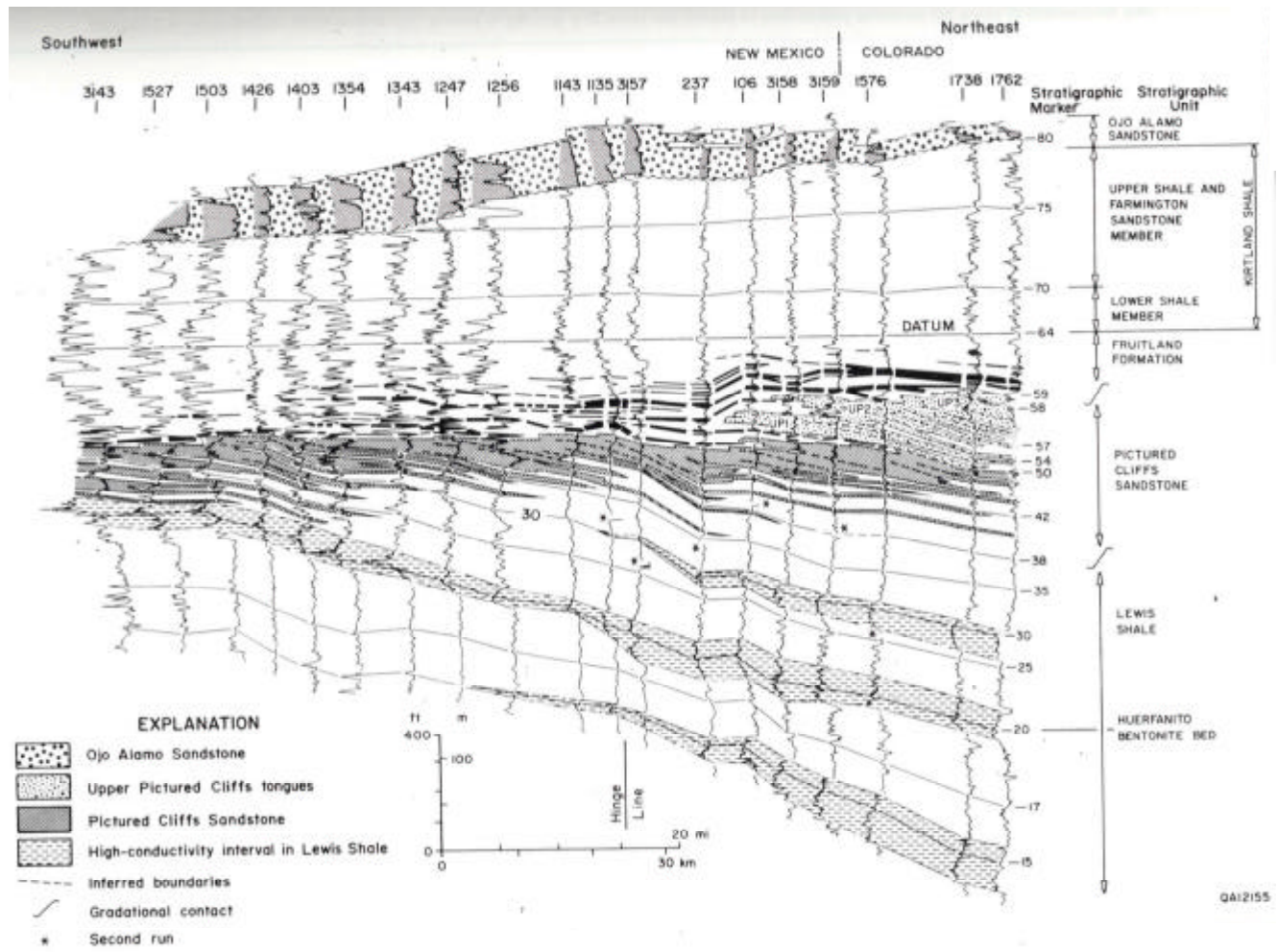
(From Ayers et al., 1994)

Figure 3.5.
San Juan Basin Structural Hingeline
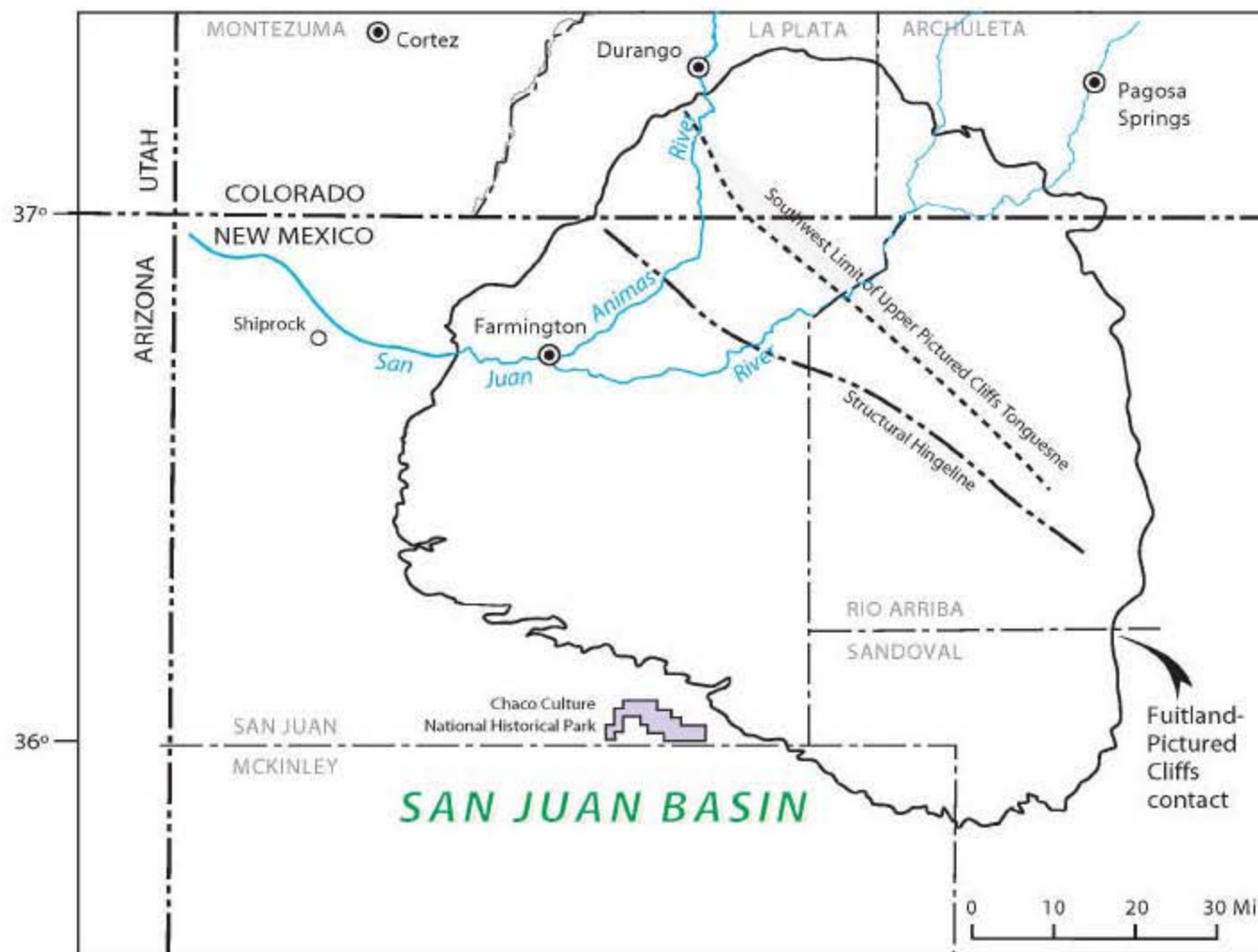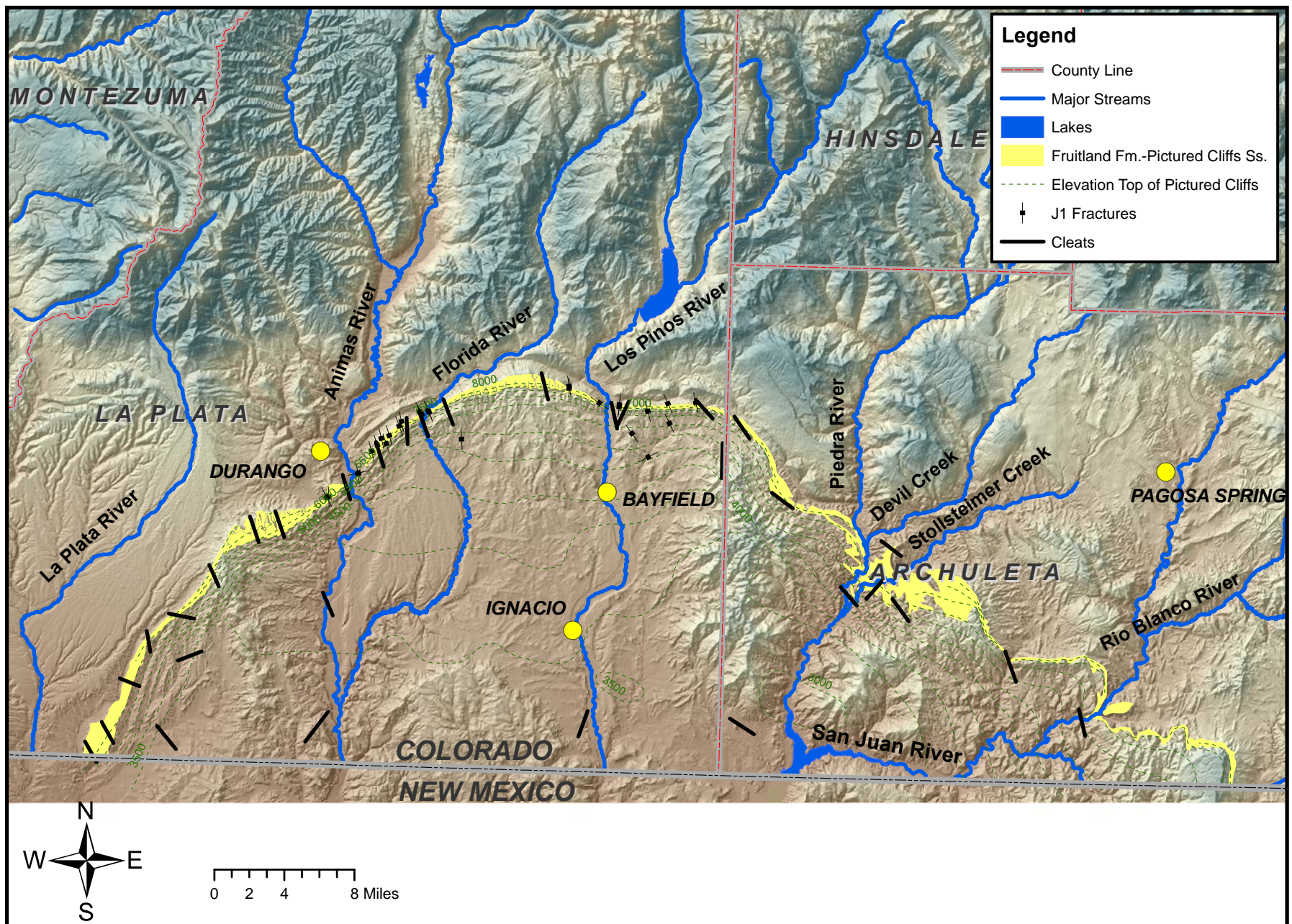
Figure 3.6. J1 Fracture and Coalbed Face Cleat Orientation, Northern San Juan Basin
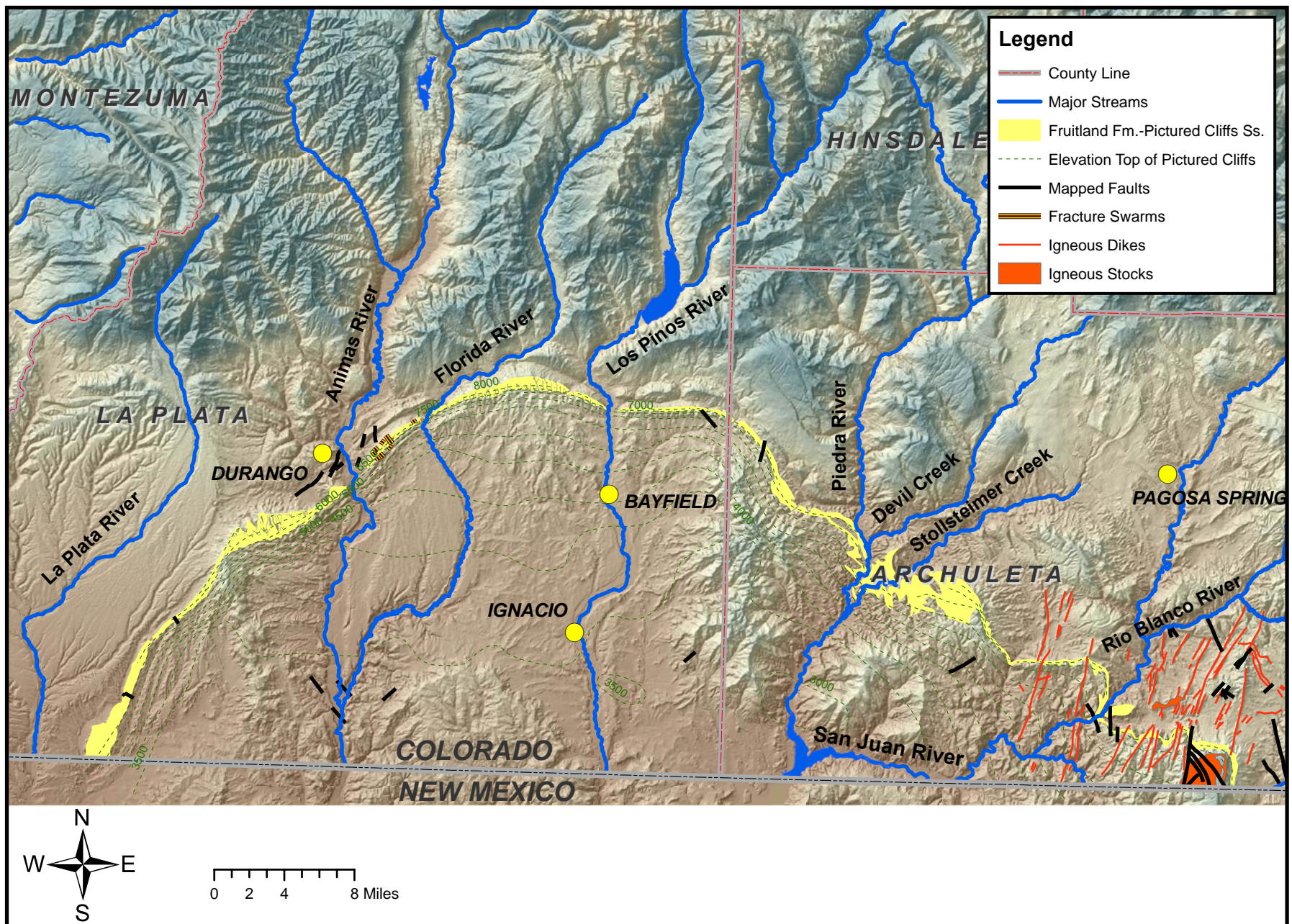
Figure 3.7. Faults, Fracture Swarms and Igneous Intrusions Affecting the Fruitland Formation, Northern San Juan Basin

Figure 3.8.
Fruitland Formation Coal Intervals Along the Outcrop, Northern San Juan Basin, Colorado
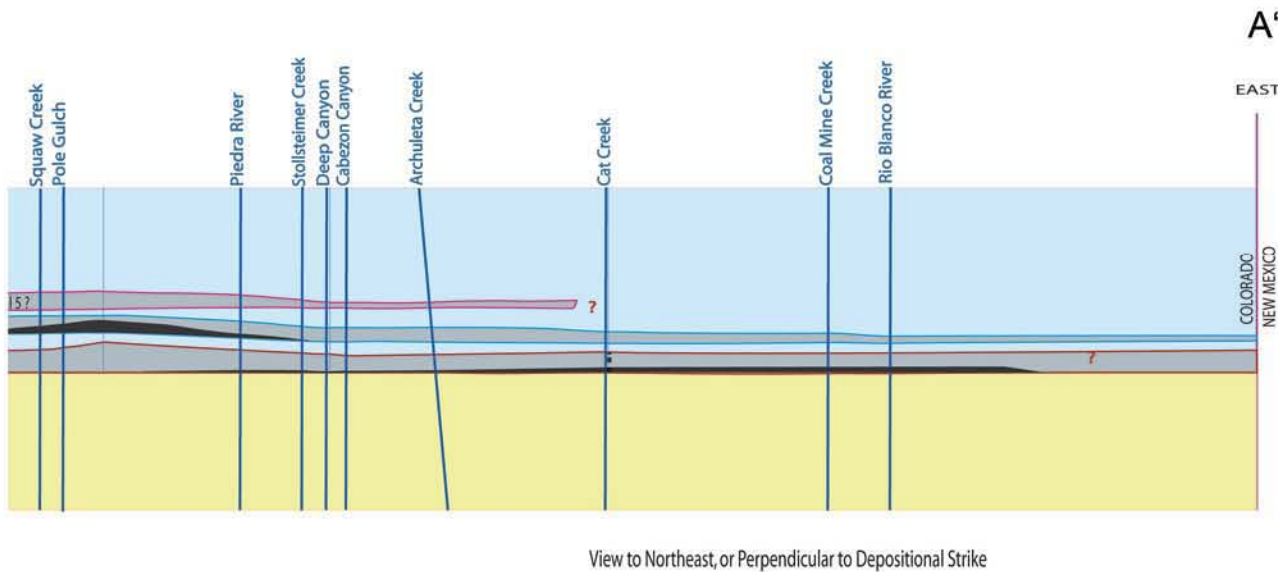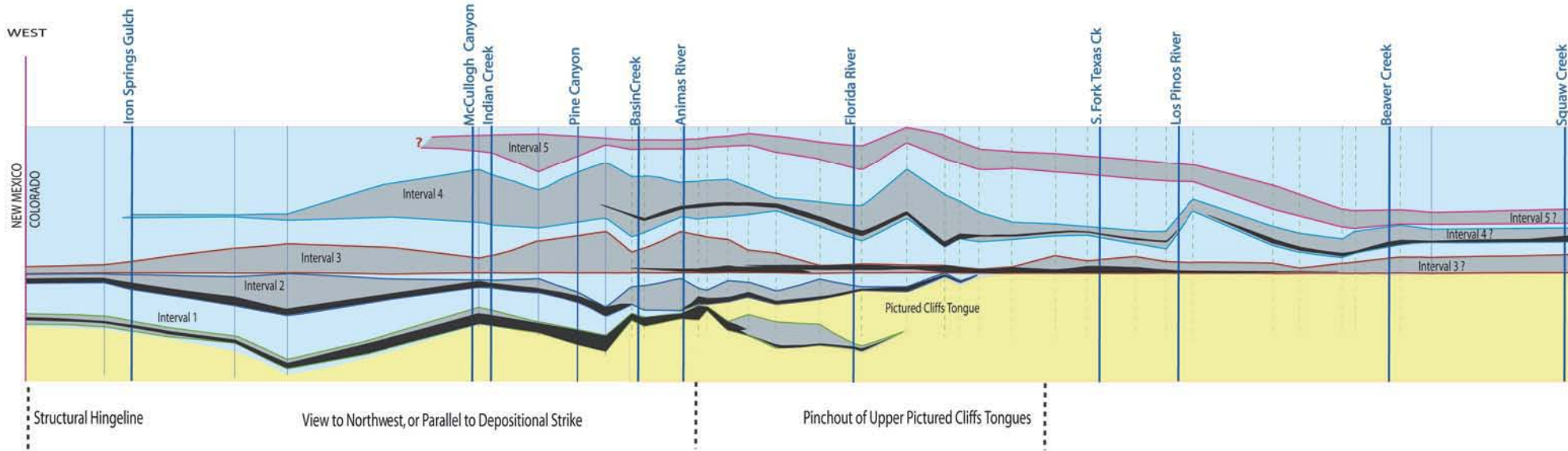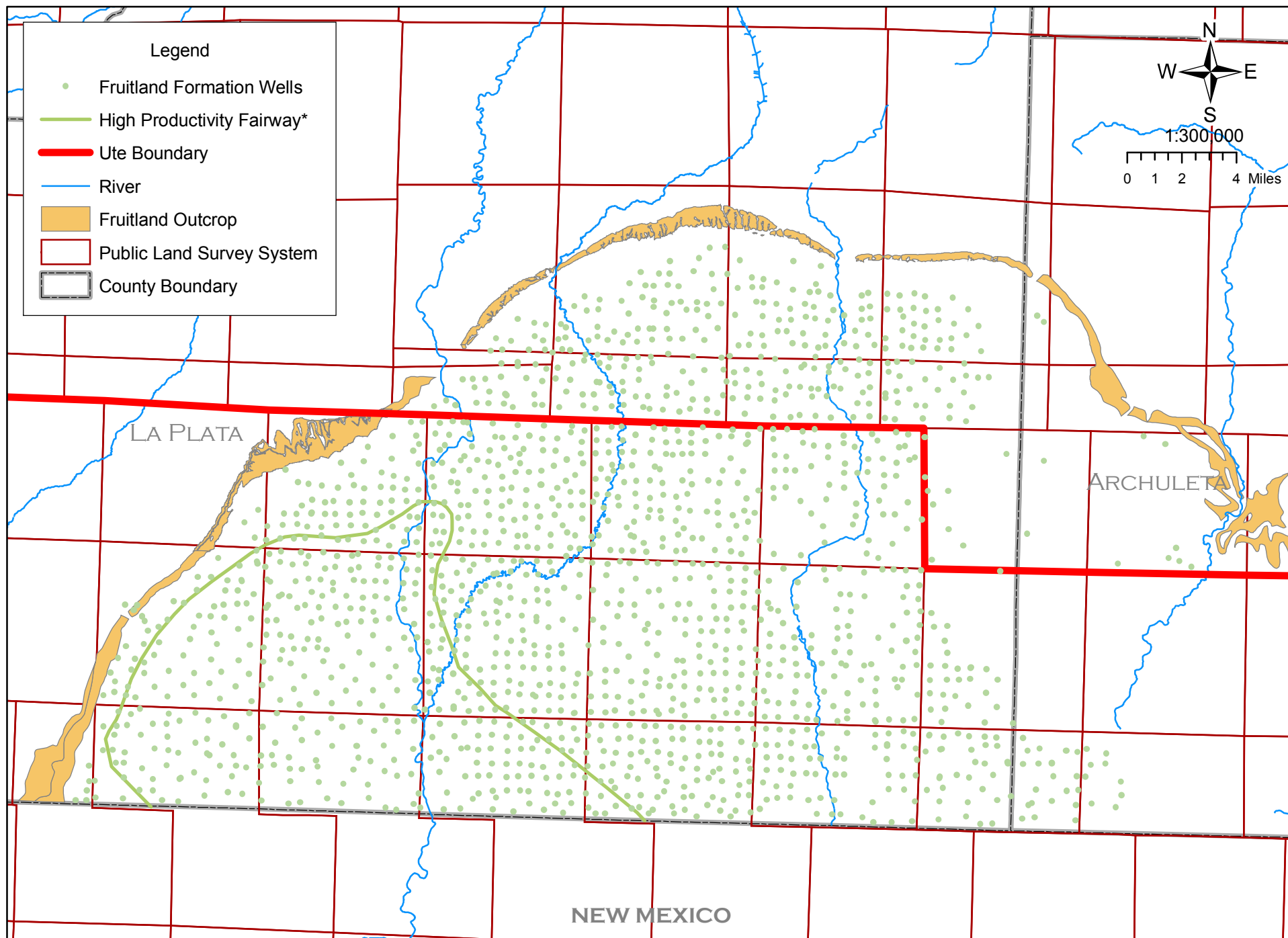
Figure 4.1. High Productivity Fairway (*Based on Tyler, 1997; Figure 7)

Legend

- Fruitland Formation Wells
- High Productivity Fairway*
- Ute Boundary
- River
- Fruitland Outcrop
- Public Land Survey System
- County Boundary

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Figure 4.2.
San Juan Basin Annual CBM Gas and Water Production Rates in Colorado

Note: Dashed line represents estimated 2005 production rates.
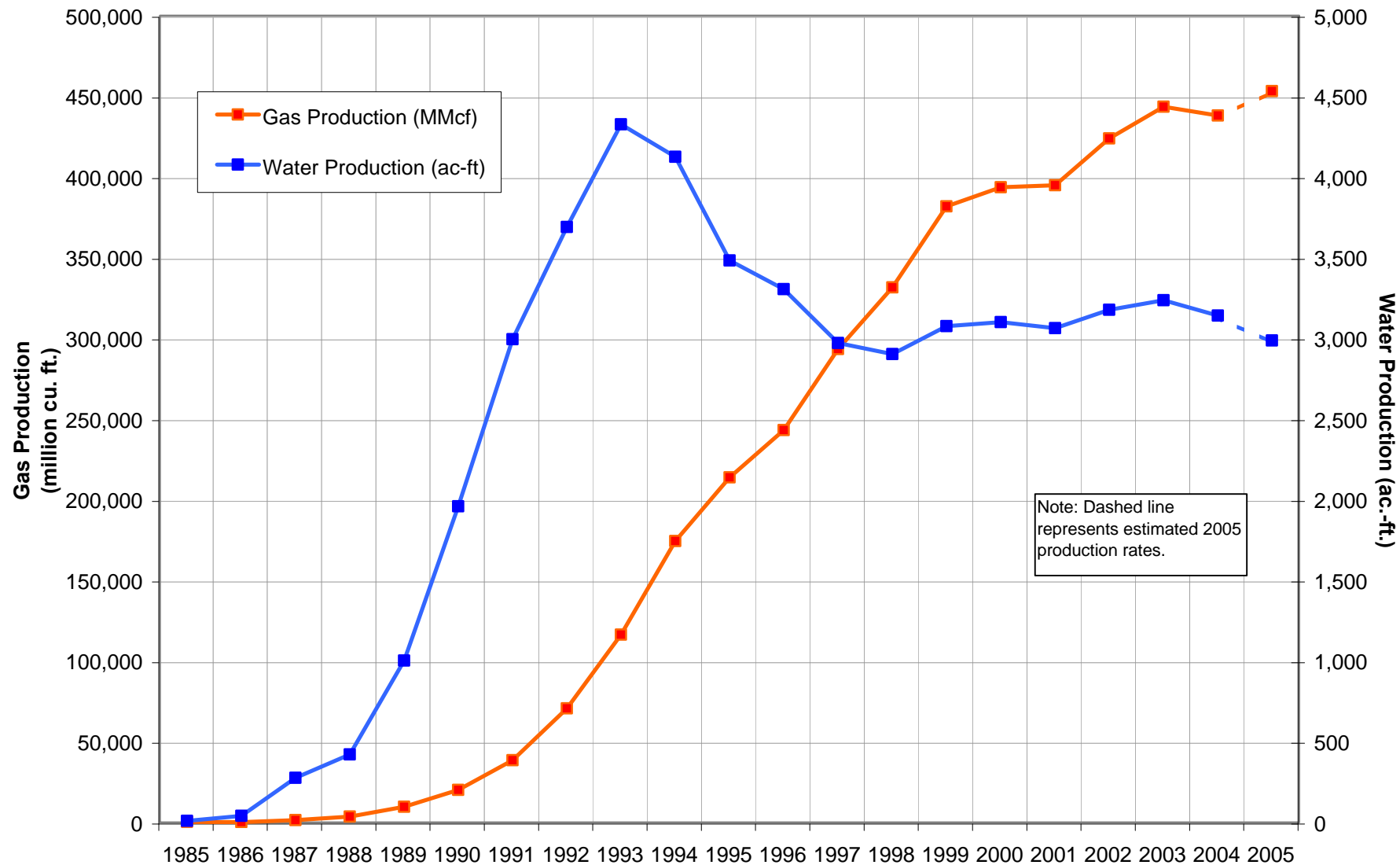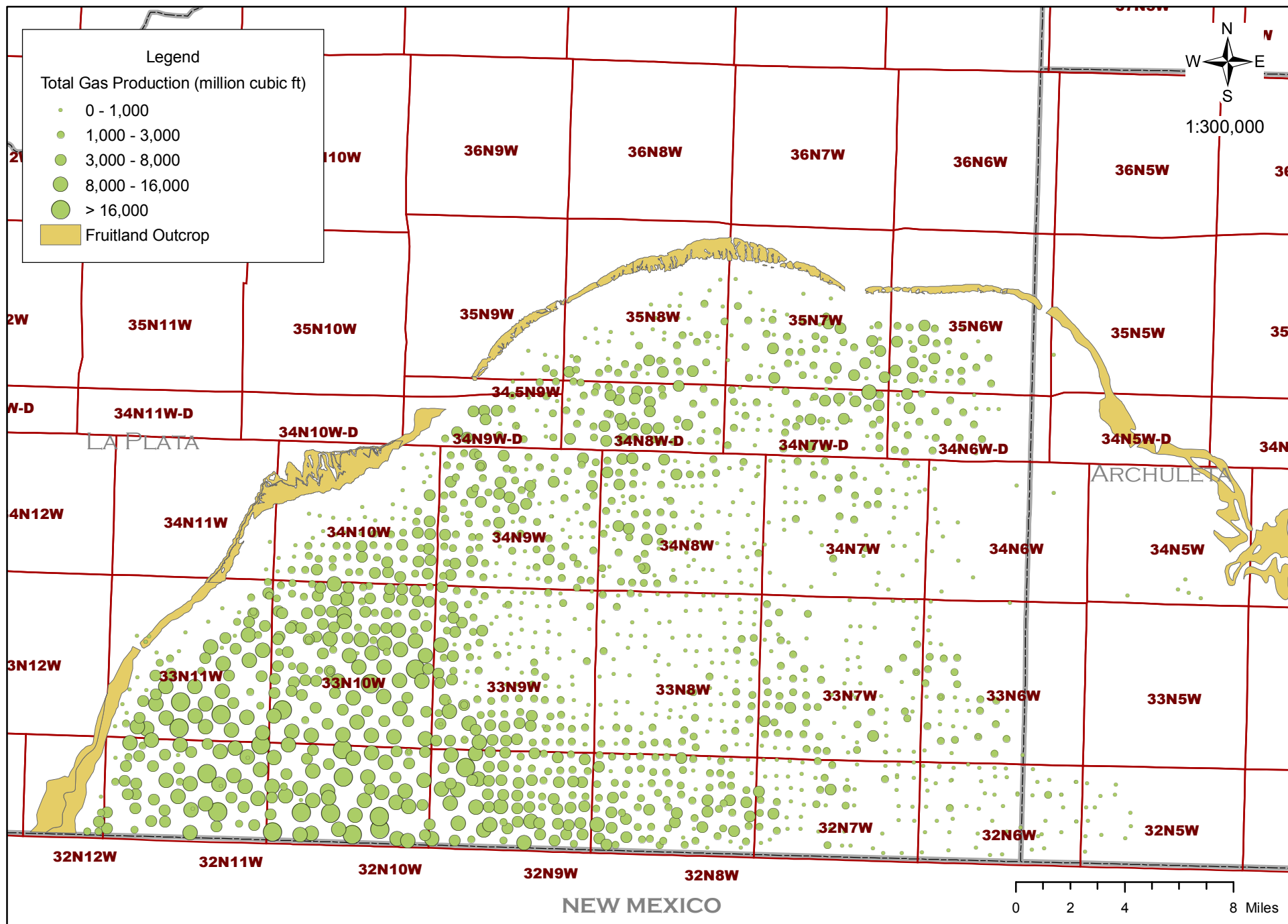
Figure 4.3. Cumulative Gas Production for Fruitland Formation Wells
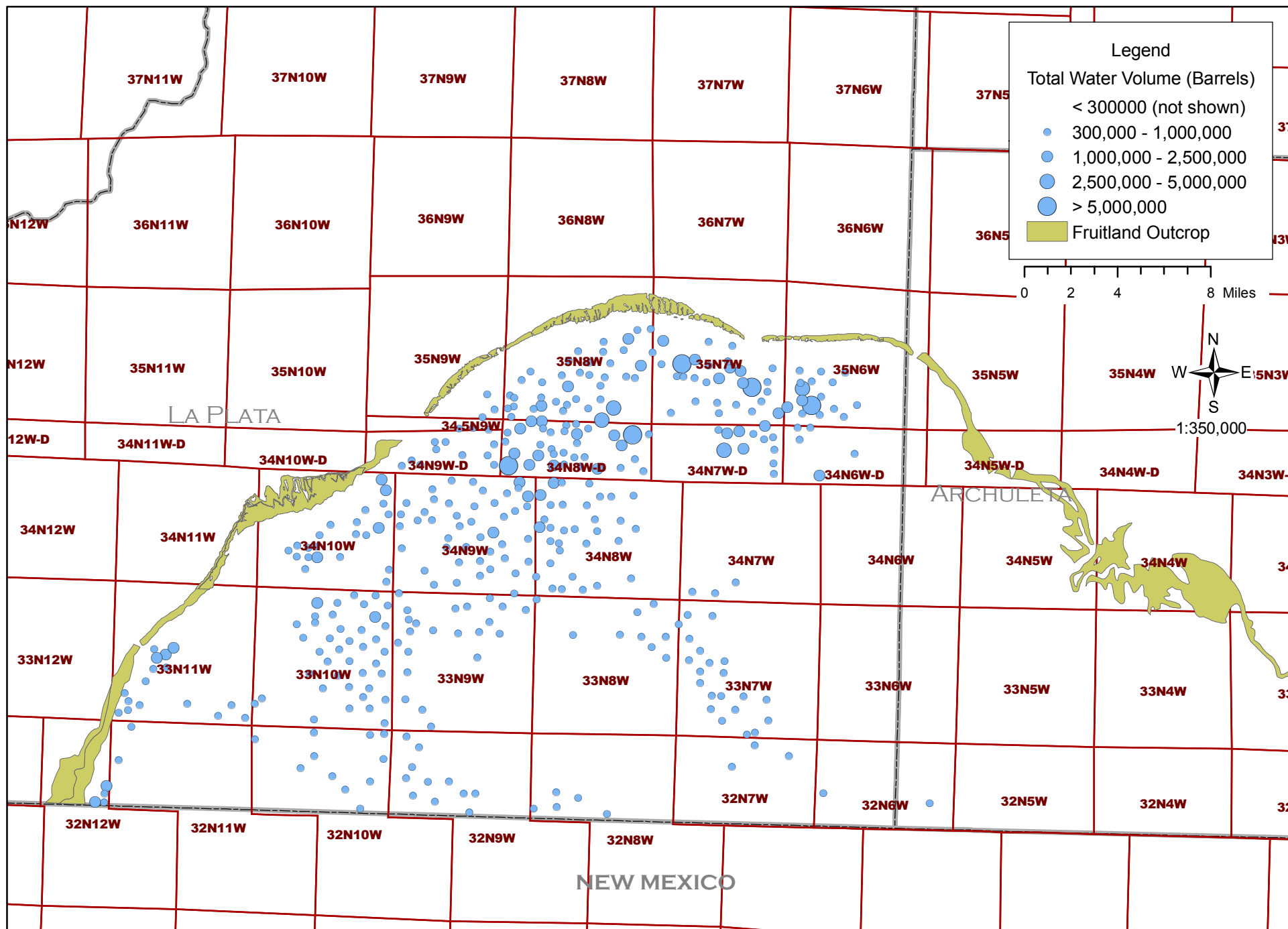
Figure 4.4. Cumulative Water Volume for Fruitland Formation Wells Installed

Figure 5.1.
San Juan Basin Schematic Cross Section Showing
Possible Groundwater Flow Paths
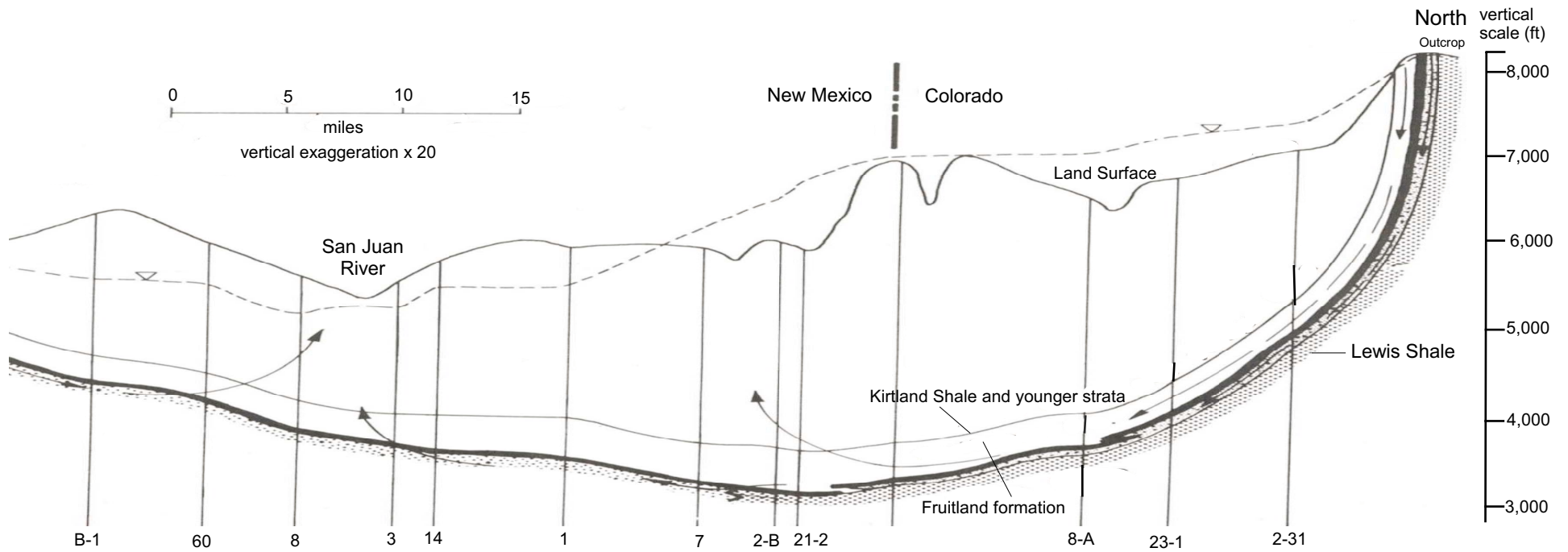
Modified from Kaiser, et al., 1994
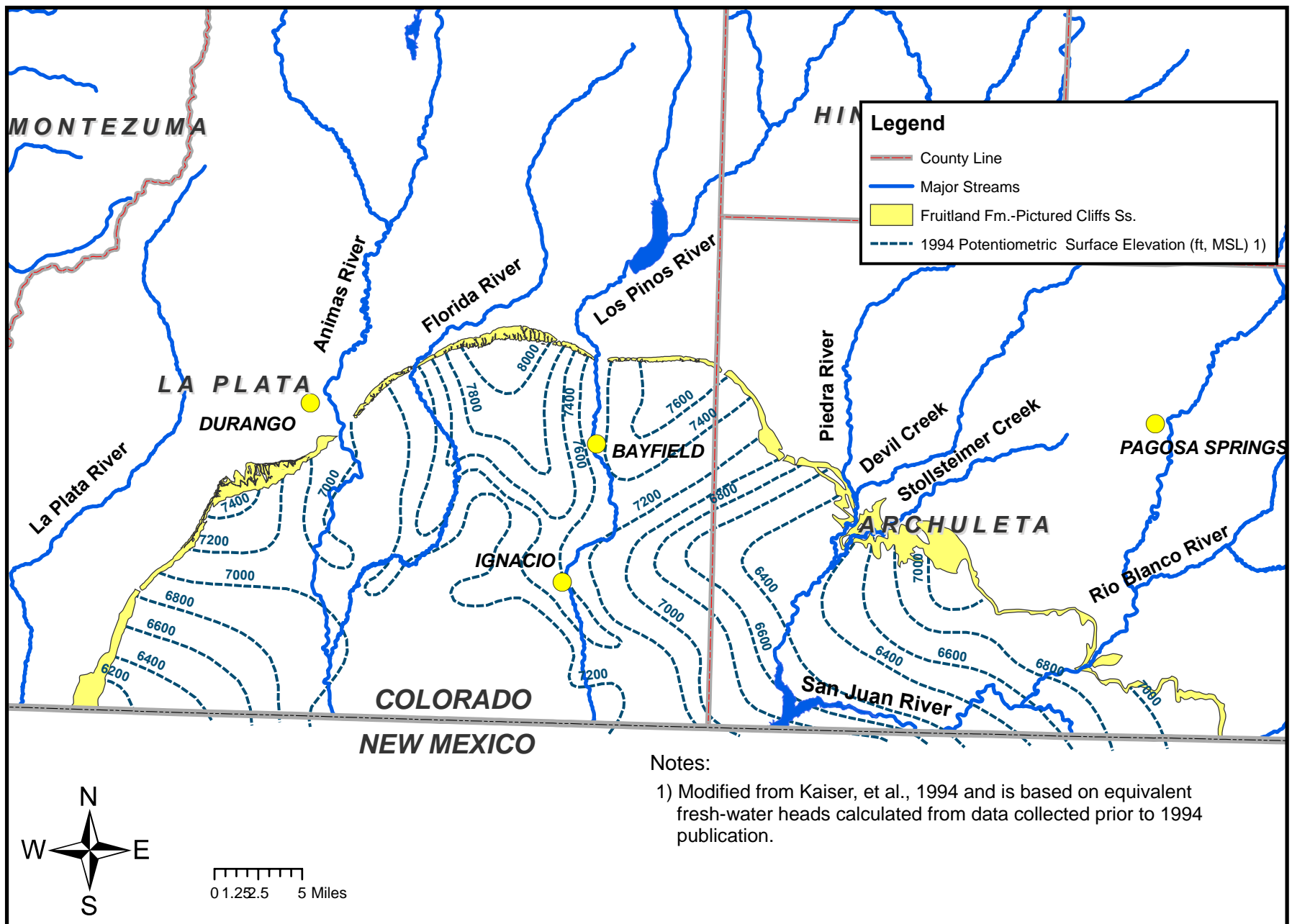
Figure 5.2. Fruitland-Pictured Cliffs Aquifer Potentiometric-Surface Map
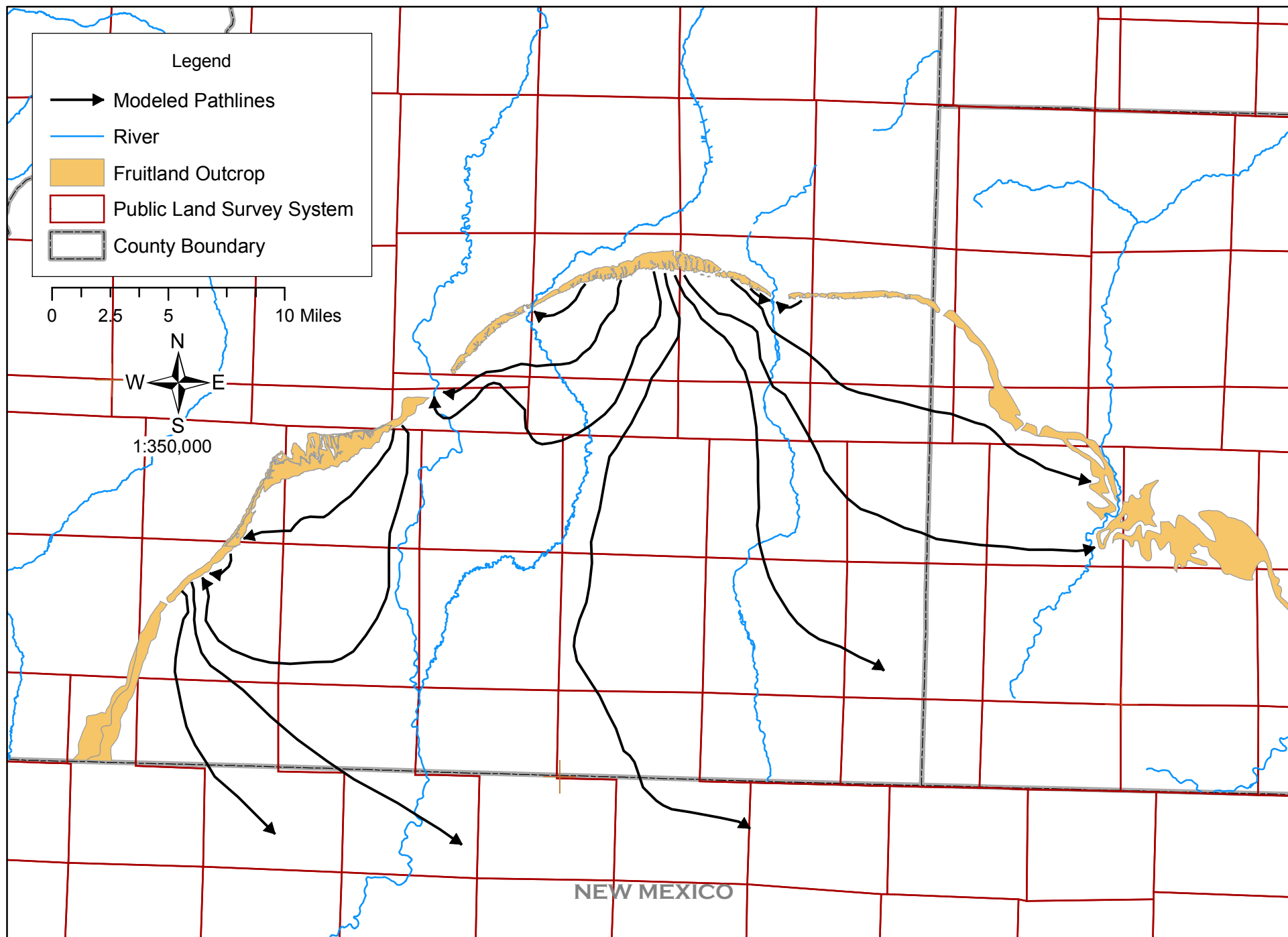
Figure 5.3. Modeled 100,000 year Flow Pathlines (modified from AHA, 2000)

Figure 5.4.
3M Groundwater Flow Model Permeability Distribution

(From AHA, 2000; Figure 6-6)

Legend

Spring Location Source
- COGCC
- Draft EIS (BLM, 2004)
- River
- Fruitland Outcrop
- County Boundary
- Public Land Survey System

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1:200,000

0 0.45 .9   1.8 Miles
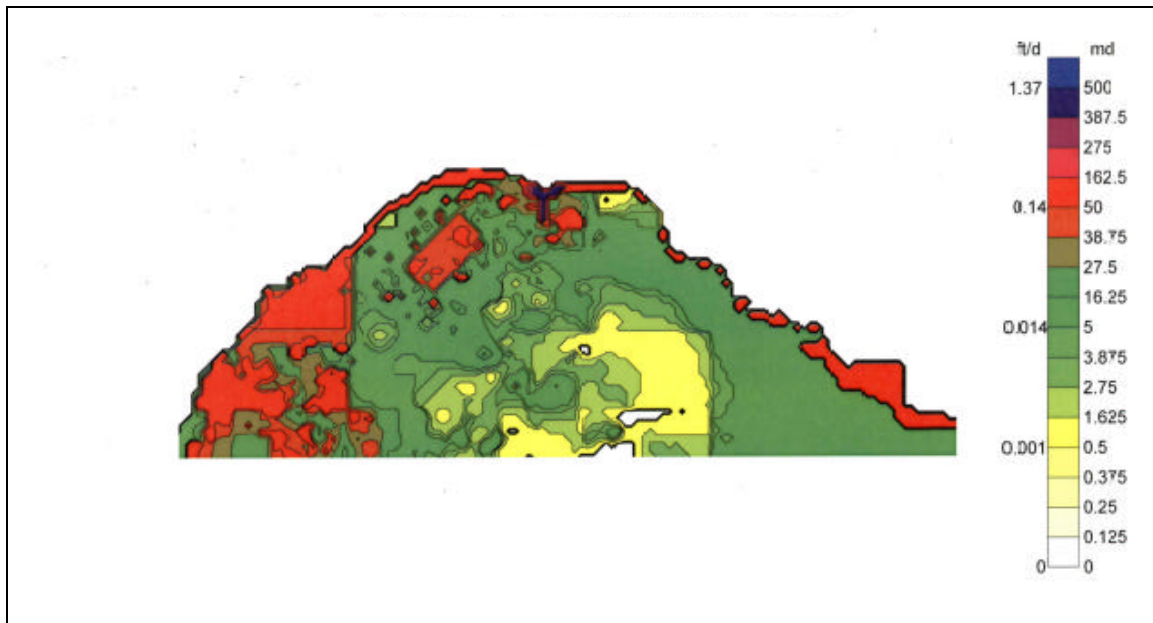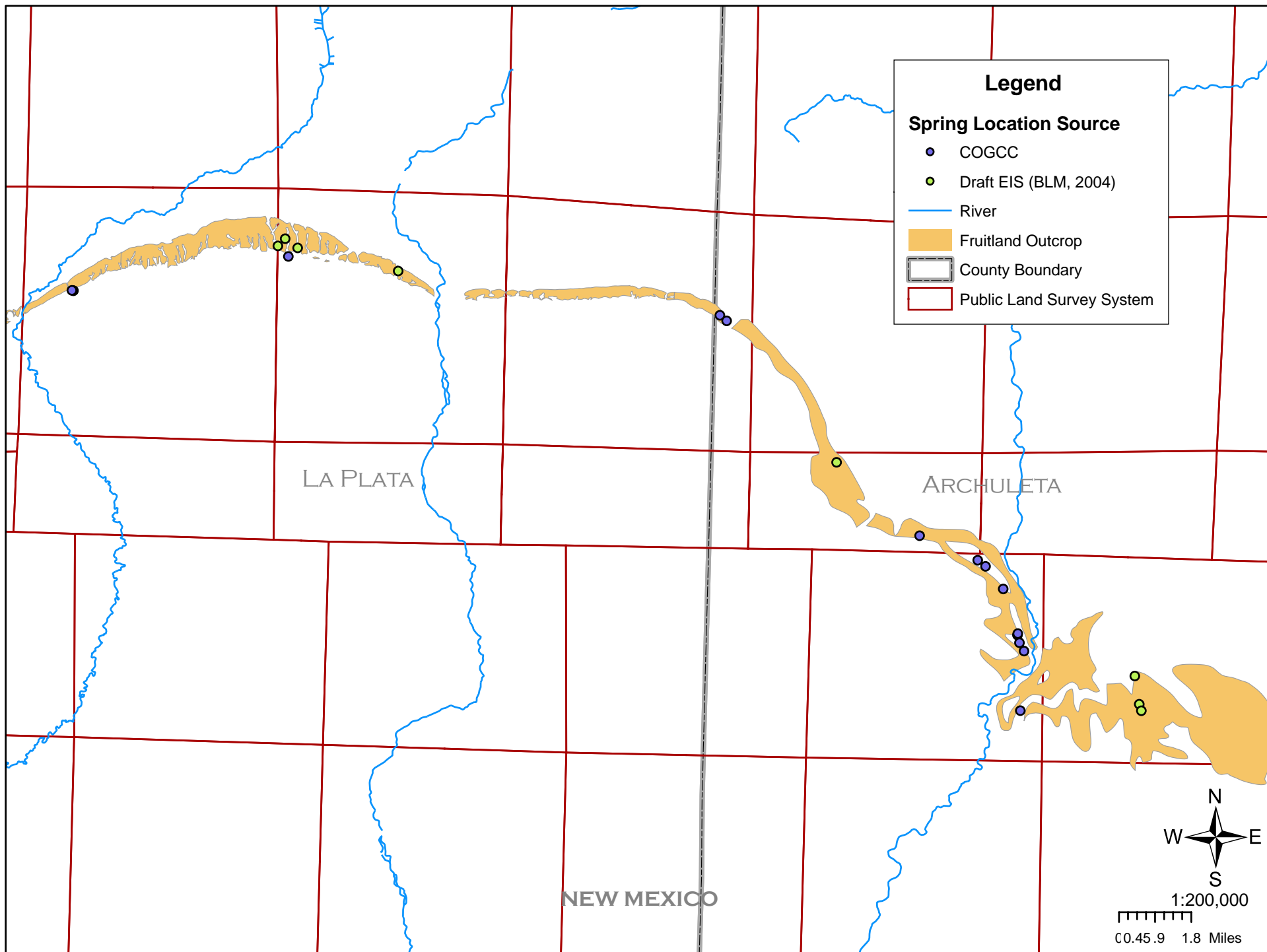
Figure 5.5. Probable Fruitland Formation Springs and Seeps
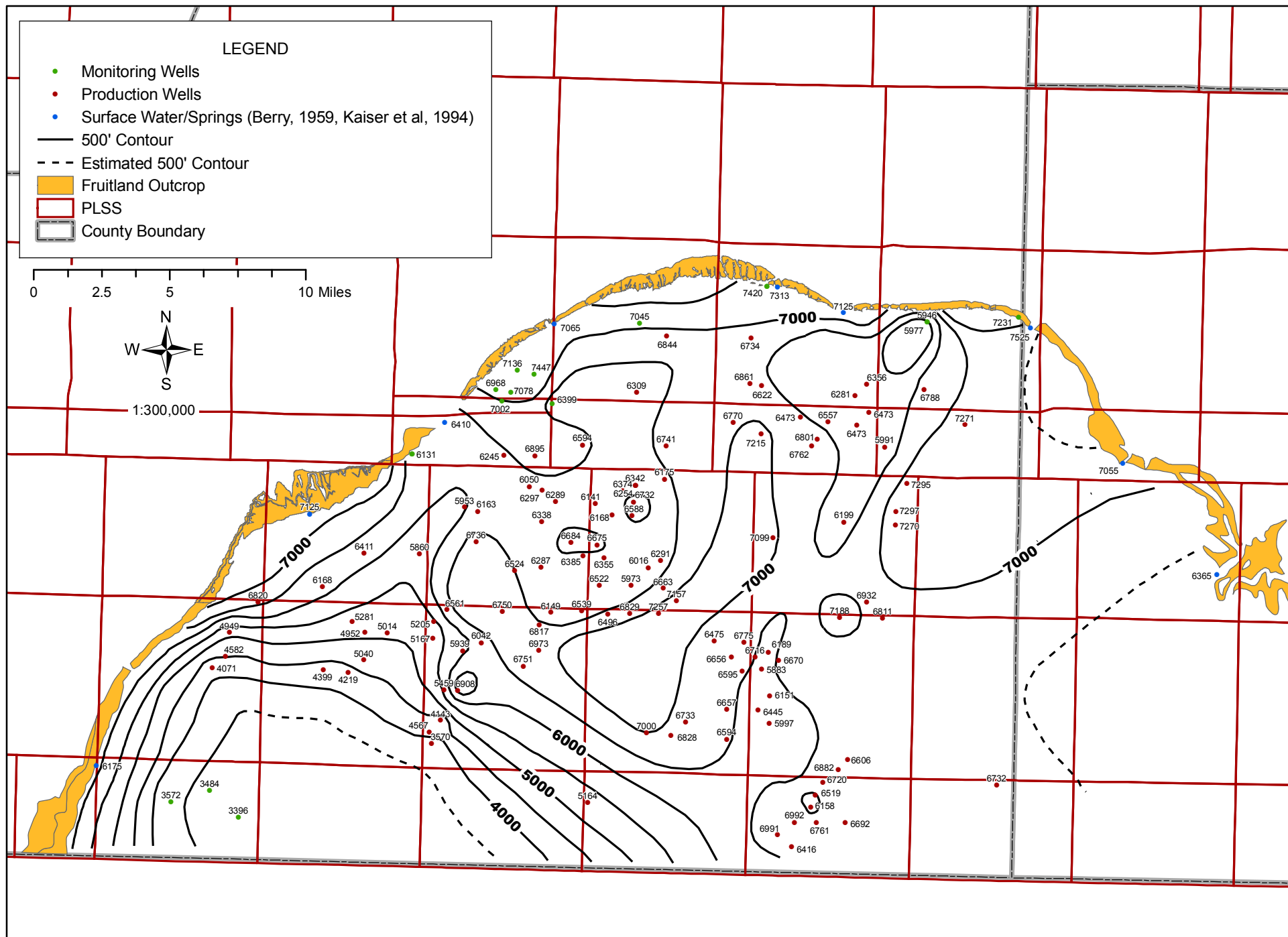
Figure 5.6. Equivalent Head Measurements
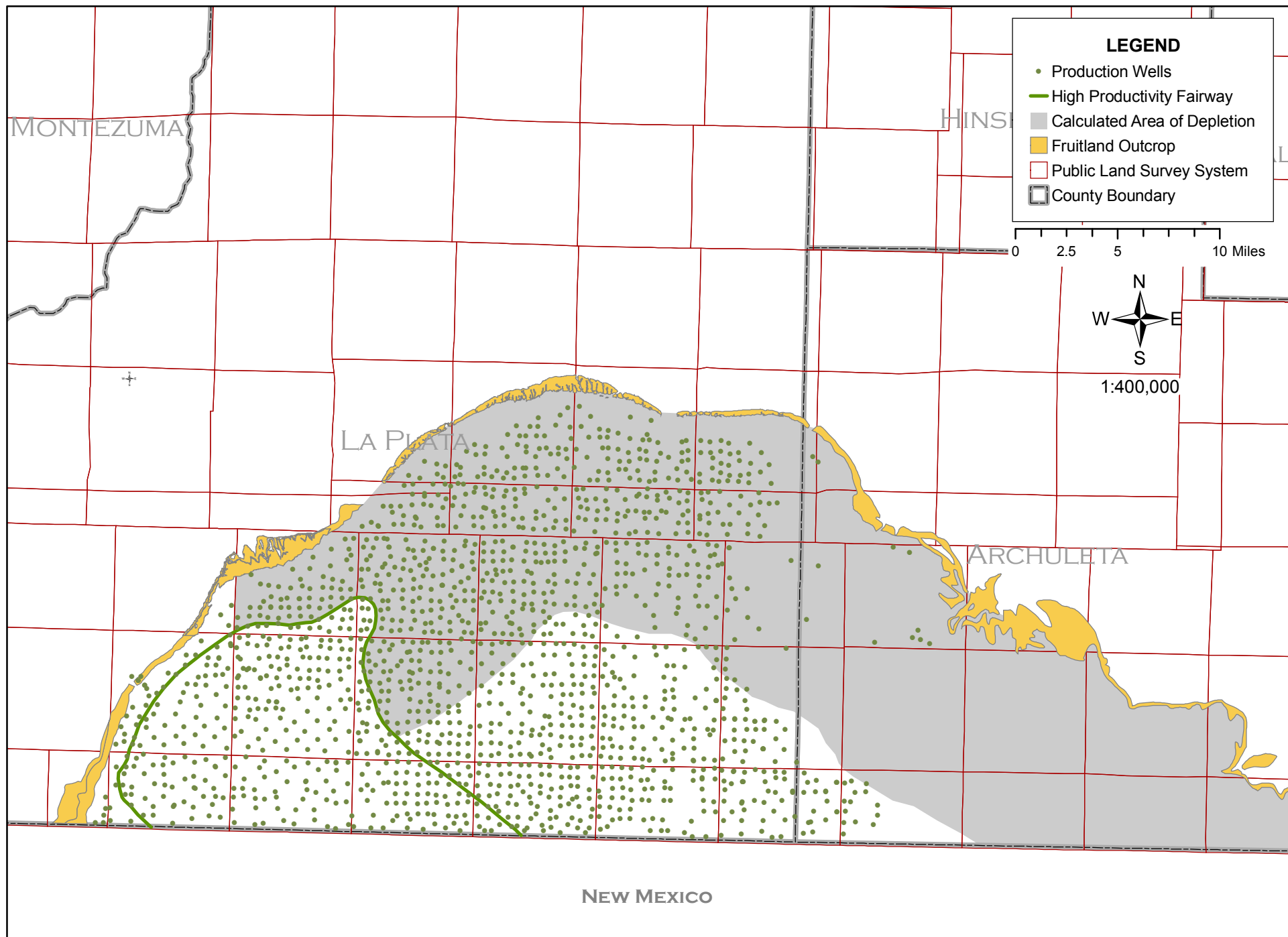
Figure 6.1. Area with Calculated Depletions exceeding 0.1% in 100 years
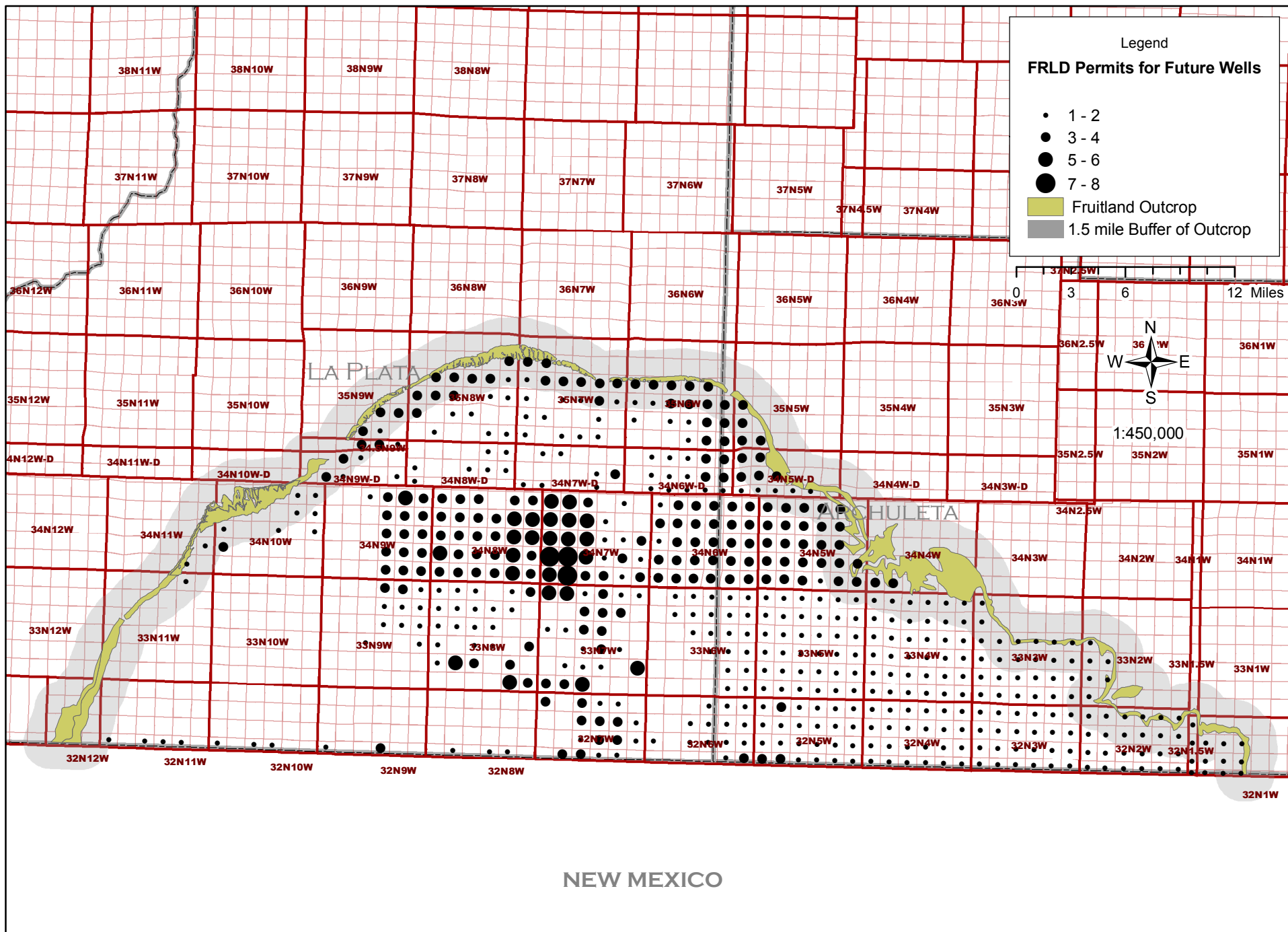
Figure 6.2. Potential Future Fruitland CBM Well Locations Used in Glover Analysis

Figure 6.3.
Net Depletions of Outcrop due to CBM Water Production

Net Fruitland-Outcrop Depletion Rate
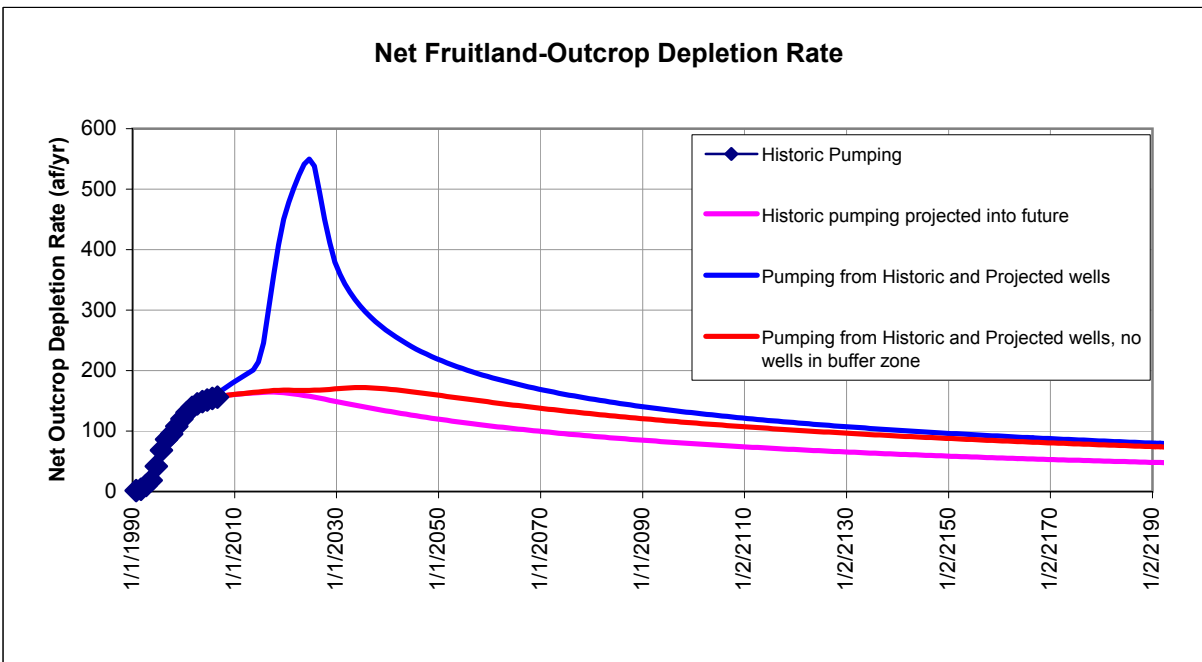
Figure 6.4.
Comparison in Depletion Rates and Timing for
Wells 1, 2, and 4 miles from the Outcrop

Net Fruitland-Outcrop Depletion Rate
Single-well Depletion Tests
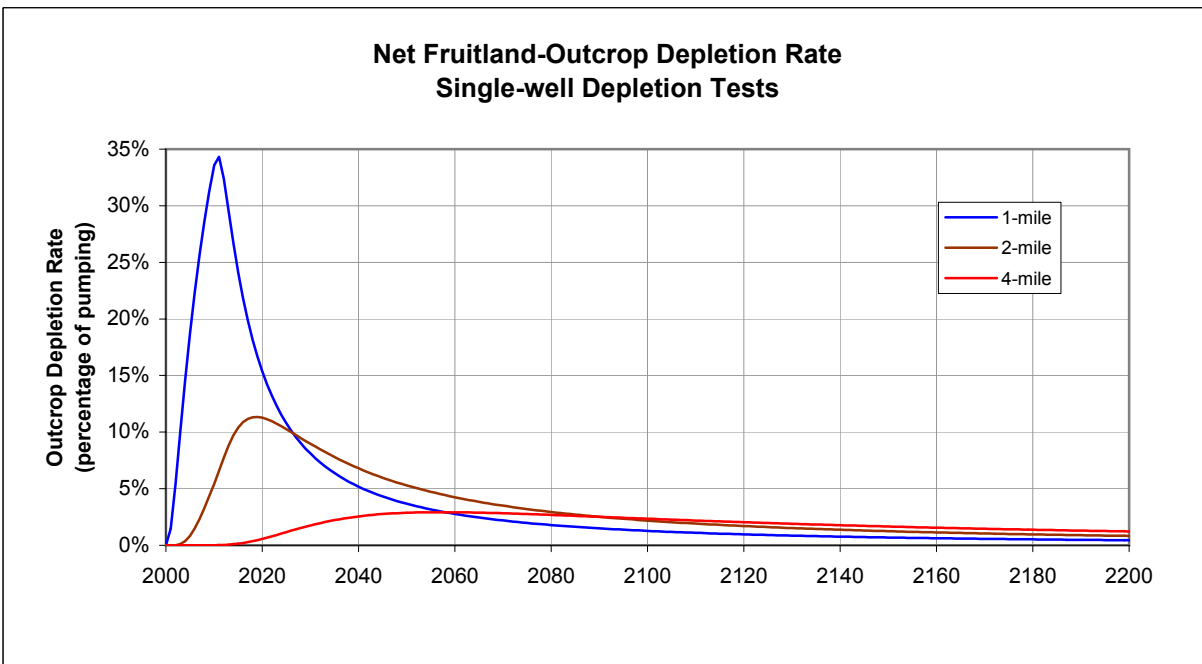
Figure 7.1.
Regulation of Water from CBM Wells

```
                    ┌─────────────┐
                    │             │
                    │  WELL HEAD  │──────── GAS SALES ────────
                    │             │
                    └──────┬──────┘
                        W  │  │
                        A  │  │
                        T  │  │
                        E  │  │
                        R  │  │
     ─────────────────────┘  └─────────────────────────
   WATER DISPOSED INTO              WATER DISCHARGED TO
   INJECTION WELL OR PIT              THE ENVIRONMENT
```
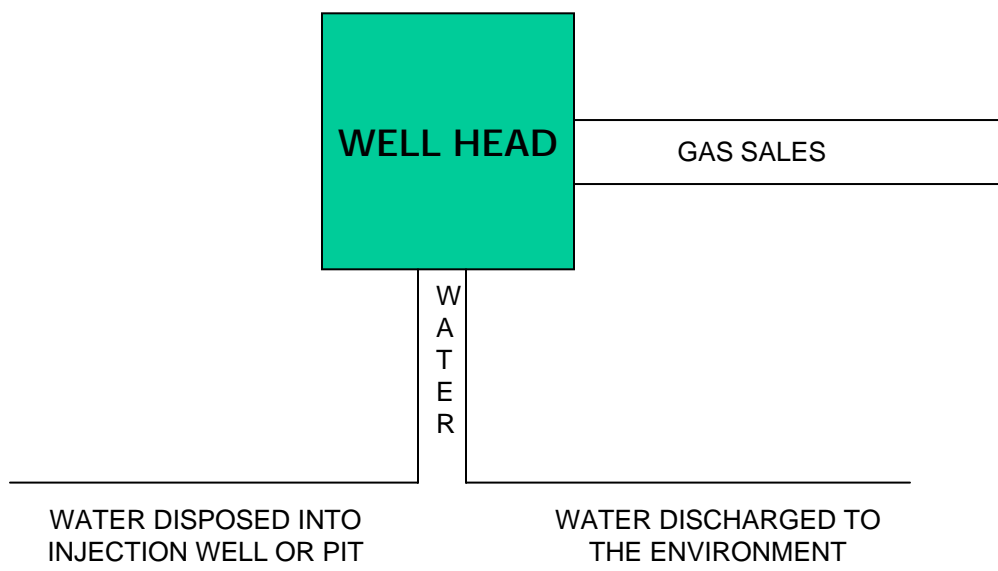
These water disposal methods are under the jurisdiction of the **OGCC**.

This method of water disposal is under the jurisdiction of the **CDPHE-WQCD** for approval to discharge water. After the water is discharged it is under the jurisdiction of the **DWR** for issues concerning water rights.

Table 3.1.
Fruitland Coalbed Physical Characteristics[1]

	Range		Median	Standard Deviation
Coal- bearing Interval Thickness (ft)	39	to 467	243	101
Number of Coal Seams	3	to 13	7	2
Net Coal Thickness (ft)	12	to 136	58	25
Separation Between Coal and Pictured Cliffs (ft)	0	to 60	2	14

[1] Data is based on both outcrop observations and geophysical well log analysis.

Table 3.2.
Fruitland Coal Bearing Interval Properties near the Outcrop

Section [1]	Location [2]	Nearest Stream	Coal-Bearing Interval Thickness	Coal Intervals	Number of Coal Beds	Net Coal Thickness	Separation of Coal from Pictured Cliffs [3]
Carbon Jnct. 1	34N, 9W sec 4	Animas River	262	I1-I4	6	85	2' siltstone
First Flatiron 1	35N, 9W sec 33	Animas River	226	I1-I3	7	43	Kpc Tongue 60' None No coal in I1
Fuel Resources SE Durango Fed 34.5-34-1	34.5N, 9.5W sec 34 Dip 8	Animas River	274 *(271)*	I2-I4	12	82 *(81)*	Kpc Tongue 2' shale Kpct- I2 No coal in I1
Horse Gulch 1	35N, 9W sec 24	Florida River	467	I1-I5 (I4 covered)	5	12	None Int 2 w/ Kpct Kpc Tongue 129' 8' covered Kpc-I1 6' coal in I1
Huber Corp.Huber Federal 2-29	35.5N, 8.5W sec 29 Dip 8	Florida River	413 *(409)*	I2-I5 (I1 Not logged) (No coal in I2)	11	64 *(63)*	Kpc Tongue 91' 110' Kpct-I3
Edgemont Ranch 1	35N, 8W sec 17	Florida River	332	I2-I4 (I1 pinched out) (I3 covered)	5	25	Kpc Tongue 15' 1' siltstone Kpct-I2
Amoco Prod Garcia Gas Unit 1	35.5N, 8.5W sec 21 Dip 5	Florida River	420 *(418)*	I1-I5	8	58 *(58)*	Kpc Tongue 117' 1' shale Kpc-I1 48' shale Kpct-I2
Pine River Ranches 1	35N, 7W sec 14	Los Pinos	235	I3-I5 (I1&I2 pinched out)	4	15	Kpc Tongue to base 2' siltstone Kpct-I3
Amoco Huber-Wilbourn 1-18	35N, 7W sec 18 Dip 16	S. Fork Texas Creek	270 *(260)*	I3-I5	10	65 *(62)*	Kpc to base None
HuberJM Huber/SPC Federal 2-13	35N, 8W sec 13 Dip 17	S. Fork Texas Creek	314 *(300)*	I3-I5	9	75 *(72)*	Kpc to base 37' shale
Amoco Prod State of Colo AX-1	35.5N, 7.5W sec 16 Dip 15	S. Fork Texas Creek, Los Pinos	199 *(192)*	I3-I5 (I1&I2 pinched out)	6	48 *(46)*	Kpc to base None Kpct-I3
Severn Peak 2/La Plata County Line	35N, 6W sec 15	Wickerson Gulch, Beaver Creek	160	I3-I5 (I1&I2 pinched out)	8	54	Kpc to base 8'shale and 12' covered Kpct-I3
Amoco Miller GU-1	35N, 6W sec 21 Dip 17	Beaver Creek	232 *(222)*	I3-I5 (I1&I2 pinched out)	8	69 *(66)*	Kpc to base 4'shale Kpc-I3
Amoco USA Amoco Com AC 01	35N, 5W sec 30 Dip 17 (est)	Beaver Creek	150 *(143)*	I4-I5 (Possibly I3)	5	61 *(58)*	Kpc to base None or 2' silt Insufficient log
BP America Federal No. 10U A-1	34N, 5W sec 10 Dip 17 (est)	Piedra River	123 *(118)*	I4-I5 (Possibly I3)	6	57 *(54)*	Kpc to base 33' shale-silt
BP America Federal No. 32A No. 1	34N, 4W sec 32 Dip 10 (est)	Stollsteimer Creek	88 *(87)*	I3-I5	4	32 *(32)*	Kpc to base None Kpct-I3
Amoco Felix Gomez No.1	33N, 3W sec 32 Dip 10 (est)	Rio Blanco	40 *(39)*	I3-I4 (I5 no coal)	3	24 *(24)*	Kpc to base None Kpct-I3

Notes
1. Entries in italics are from borehole geophysical logs; otherwise entries are from measured sections.
2. For geophysical logs, actual coal seam thicknesses are calculated assuming that the boreholes are vertical.
3. As described in measured sections; for geophysical logs, shale may include siltstone.

Table 5.1.
Wells with High-Frequency Data Used in Model Calibration

Site Name	Site Well Number	Location		API #	Period of Record
		Township	Range		
Basin Creek	MW 34-9-7-1	34N	9W	08815	11/2001 - 7/2005
Basin Creek	MW 34-9-7-2	34N	9W	08804	5/2002 - 7/2005
South Fork Texas Creek	MW 35-7-8-1	35N	7W	08801	11/2001 - 7/2005
South Fork Texas Creek	MW 35-7-8-2	35N	7W	08811	11/2001 - 7/2005
Beaver Creek Ranch	MW 35-6-17-1	35N	6W	08802	5/2002 - 7/2005
Beaver Creek Ranch	MW 35-6-17-2	35N	6W	08814	11/2001 - 7/2005
Shamrock Mines	MW 35-6-13-1	35N	6W	08805	5/2002 - 7/2005
UTE 32-11 POW	1	32N	11W	07958	1/1999 - 8/2005
UTE 32-11 POW	2	32N	11W	07959	1/1999 - 8/2005
UTE	17	32N	11W	07054	7/1999 - 10/2005
SOUTHERN UTE	10-3	33N	11W	07120	1/1999 - 8/2005
Day-V-Ranch 34 1/2 #35-1	35-1	34.5N	9W	07468	11/2003 - 8/2005
Federal #34-1	34-1	35N	9W	07615	10/2001 - 8/2005
Day-V-Ranch #35-2	35-2	35N	9W	07494	10/2001 - 8/2005
State #36-3	36-3	35N	9W	07467	12/2000 - 8/2005
Day-V-Ranch #1-35	1-35	35N	9W	06894	10/2001 - 8/2005
Garcia	1-22	35N	8W	07549	12/1997 - 10/2004
Marie Shields	1	34N	8W	06908	2/1996 - 10/2004
Gurr Federal Gas Unit	1	35N	7W	07193	1/1997 - 12/2005

Table 7.1.
Requirements and Potential for Beneficial Use of CBM Produced Water in the San Juan Basin in Colorado

Beneficial Use	Approximate TDS Requirements	Area Meeting TDS Requirements[1]	Local Use or Via Conveyance[2]	Estimated Demand/Economic Viability
Domestic water supply	<500 mg/L (up to 1000 mg/L occurs)	Little to none; only adjacent to outcrop	Local use	Low-moderate demand; locally viable in very small area
Municipal water supply	<500 mg/L	None; only adjacent to outcrop	Conveyance	Low demand and economic viability due to available surface water
Industrial use	Varies, treatment often required	Appx. 260 mi^2 is <10,000 mg/L	Conveyance (or local if new development)	Low demand and economic viability without new industrial development
Mining	Varies, treatment may be required	Appx. 260 mi^2 is <10,000 mg/L	Conveyance	Very low unless development of coal mining
Irrigation	<3000 mg/L	Appx. 25 mi^2	Local use or minimal conveyance	Unknown, possibly medium to high demand; is locally viable
Livestock watering	<7000 mg/L	Appx. 90 mi^2	Local use or minimal conveyance	Unknown, possibly medium demand; is locally viable
Poultry watering	<3000 mg/L	Appx. 25 mi^2	Local use or minimal conveyance	Unknown; without treatment, is viable only for a small area
Fire protection	NA	All of basin	Local use	Demand is seasonal, and probably low overall
Dust suppression	NA	All of basin	Local use	Demand is localized, and probably low.
Minimum streamflow	Est. <600 mg/L; see also 5CCR 1002-34[3]	None; only adjacent to outcrop	Local use or conveyance	Low, not an issue in the basin
Augmentation	Based on use and point of discharge	Unknown, depends on use	Local use or conveyance	Currently low; potentially high if CBM water production is regulated.
Interstate Stream Compact compliance	Est. <600 mg/L; see also 5CCR 1002-34[3]	None; only adjacent to outcrop	Local use or conveyance	Very low

Notes:

[1] Calculated to within approximately 1 mile of Fruitland Formation outcrop; uses Plate 2E in Riese et al, 2005, for delineation of TDS in basin. Does not include areas in Archuleta County.

[2] Conveyance via either stream, ditch, or pipeline.

[3] TDS not regulated directly, but other inorganic compounds, including chloride, are regulated (chloride limit is 250 mg/L where specified). TDS limits estimated based on published specific conductance measurments in streams (BLM, 2004) and non-degradation assumptions.

Appendix A

Comments Provided to Study Team Subsequent to Public Meeting

APPENDIX A
Comments Provided to Study Team Subsequent to Public Meeting

Commenter 1
Jim McCord
Hydrosphere Resource Consultants
115A Abeyta Street
Socorro, New Mexico 87801

With regard to your ongoing study of stream depletions due to CBM development in the northern San Juan Basin, I have a few concerns, including:

1. Applicability of the Glover model to actual conditions in the Fruitland, and how it is applied to this situation. For example, to evaluate stream depletions will you just evaluate impacts to the main stems of the impacted rivers (Animas, Florida, and Piedras), or will you also look at impacts to their tributaries? Another related question, how can you justify the applicability of the Glover method to a (relatively) steeply dipping aquifer that becomes confined downgradient from its recharge / outcrop zone?

2. It appears that the study will focus exclusively on depletions to river flows, and will not look at depletions to springs and seeps that occur in the vicinity of the Fruitland outcrop. The Northern San Juan Basin EIS estimated approximately 200 af/yr of impact to the streams, yet the Fruitland will be experiencing more like 3,000 af/yr of pumping/depletion. Where is the other 2,800 af/yr coming from? Isn't it likely that part will come from storage in the outcrop area, which will subsequently impact spring flows and tributary flows in the outcrop area. From the perspective of "the safe yield myth" (Bredehoeft, JD, SS Papadopulos and HH Cooper, 1982. *Groundwater: The Water Budget Myth*), any diminution of storage in the outcrop area will adversely impact water users who depend on those springflows. In a way, this can be considered analogous to concerns raised in the San Luis Valley, where the State Engineer has proposed rules that would require artesian aquifer pumpers to avoid impacting the pressure relationship between the deep artesian and the shallow unconfined aquifer (with the intent of avoiding injury to shallow, tributary aquifer water users). The analyses proposed for your study fails to account for this mode of injury to existing vested water rights.

I recognize that your current project has a fairly limited scope, but would appreciate it if you could at least comment on these issues in your final report.

Commenter 2
James and M. Theresa Fitzgerald
1028 CR 525
Bayfield , CO 81122

Please consider the following comments concerning the CBM Stream Depletion Assessment Study:

The scope of the proposed study is well beyond the resources and time proposed by DNR. For example under VI.B. Geology it is stated that "the geology will be adequately characterized to facilitate...the location or locations of nontributary areas within the basin." Under current Colorado law all water in the San Juan Basin is considered tributary. The legal standards of proof to change that designation are very high. It would be a serious affront to the holders of water rights in the San Juan Basin to try to make those

changes on the basis of a two-month review of existing research. On the Piedra Basin there is no existing research.

Secondly, the format and design of the study greatly favor the needs of the oil and gas industry to the detriment of farmers, ranchers, and other water users in the San Juan Basin.For example under section IV. Communications/Outreach all descriptions of the proposed "open communication with those we serve" refer only to "the involvement of those who develop and produce gas and oil resources." The consultant is advised "to successfully pkan and coordinate meetings between the industry and the respective agencies of DNR..." Nowhere is the public mentioned. Accordingly the Papadopulos meeting in Durango was not noticed in the Durango Herald or other local media and there was very little attendance by the general public.

Furthermore the proposed study does not allow time and resources to meet with any of the water rights holders in La Plata County whose water has been negatively impacted by CBM.

The study is an obvious attempt by DNR to assist the CBM industry in its ongoing degradation and depletion of the water of this area and to avoid its responsibility to protect the welfare of the citizens of La Plata County.

Commenter 3
Janice C. Sheftel
Maynes, Bradford, Shipps and Sheftel, LLP
West Building-835 E 2nd Avenue, Suite 123
PO Box 2717
Durango, CO 81302

Maynes, Bradford, Shipps and Sheftel, LLP, represents the Southern Ute Indian Tribe ("Tribe"). The Tribe, as you know, has a major interest in CBM production. The Tribe, therefore, is concerned about the methodology of the Study, as described at the meeting in Durango, Colorado on October 23, 2005. The results of the use of the simple and unsophisticated Glover model described at the meeting concerns the Tribe because inaccurate results might prejudice the Tribe's significant CBM development.

As you aware, the Tribe was an interested party in the study entitled, <u>San Juan Basin Ground Water Modeling Study: Ground Water – Surface Water Interactions Between Fruitland Coalbed Methane Development and Rivers</u>, prepared principally by Questa Engineering Corp. and Applied Hydrology Associates, Inc (Q/AH Study"). The Q/AH Study modeled the surface and ground water interactions associated with CBM development in the northern San Juan Basin of Colorado. It is my understanding you have a copy of the Q/AH Study.

The Q/AH Study developed multi-layer models at the intersections of the Animas, Florida and Pine Rivers with the Hogback Monocline. The Piedra River area, however, was not modeled because of lack of geologic and reservoir information. Each model area encompassed a river crossing, adjacent outcrop areas, and several square miles of active CBM production regions within the basin. Using the coal stratigraphy work performed by the Colorado Geological Survey, coalbeds were modeled by separating coals in up to 5 "packages" or layers. The intervening strata were also grouped and assigned to layers. As we understand, the recently proposed model that will be used in the Study will consider all sandstones and coals as only one layer. Furthermore, the simplistic Glover model will take into account neither the structural configuration of the monocline nor the desorbed gas component of the coal reservoir.

For the Q/AH Study, MODFLOW (hydrologic modeling software similar to the Glover model) was used to define hydrologic conditions prior to CBM development. The MODFLOW results then provided input

parameters to a reservoir model used to simulate simultaneous gas and water flow with relative permeability effects associated with 2-phase flow in an unconventional gas desorption type reservoir. Both models were conducted respectively by a senior hydrologist and a senior reservoir engineer. The sophisticated Q/AH Study determined that CBM development will deplete by 2050, surface flows fro the Animas, Pine and Florida of a maximum of 140 acre/feet/year with an additional depletion of 15-60 AF/year for the Piedra.

The Tribe is concerned that if, because the Study, with its much less sophisticated and less accurate model, determines a much larger depletive affect on area streams, the Tribe will need to spend significant resources in a major challenge to the Study results in order to avoid prejudice to the results of the Tribe's prior Section 7 Consultations for CBM development under the Endangered Species Act. In addition, the Tribe does not understand how, if the Study determines depletions to surface streams larger than those determined in the Q/AH Study, the State will have jurisdiction to regulate Tribal CBM wells. White in the Consent Decrees entered in Case Nos. W-1603-76A-F and J, entered by the District Court, La Plata County on December 19, 1991, as a compromise settlement of the Tribe's reserved water right, the Tribe agreed to State administration of the Tribe's reserved water rights under well defined circumstances, the Tribe has never agreed to State jurisdiction over its oil and gas wells.

Thank you for your consideration of the Tribe's comments. Please do not hesitate to call if you have any questions.

Commenter 4
David R. Brown
BP America Production Company
U.S. Onshore Business Unit-HSSE
1660 Lincoln Street, Suite 3000
Denver, Colorado 80264

BP America Production Company (BP) is interested in obtaining results of the subject study currently being performed by S.S. Papadopulos and Associates, Inc. (SSPA) for review. BP attended the October 24, 2005 public meeting for this study in Durango, Colorado. At that meeting it was stated that a draft report would be available December 1, 2005, which has prompted me to write this letter. Is it possible for BP to obtain a draft for review?

BP has a vested interest in the results of the subject study. We have closely reviewed the results from the 3M study, which used the MODFLOW Numerical Model to calculate stream depletions in each of four river basins. BP has some potential concerns with the SSPA study including:

- Whether it is even possible to obtain sufficiently detailed information to pinpoint areas where stream depletion may occur.

- The applicability of the Glover Model in this study because many, if not all, of the assumptions and constraints associated with the use of this model will be violated. MODFLOW was used in the Denver basin to delineate nontributary, not nontributary, and tributary water. MODFLOW, which was used in the 3M study, is a much more sophisticated analytical tool for determining nontributary and tributary water.

- The proposed methodology represents an *a priori* assumption that all of the coalbed water is hydraulically connected when extensive scientific studies indicate this is not the case.

Please advise me when BP may obtain a copy of the draft SSPA report for review and comment.

S. S. PAPADOPULOS & ASSOCIATES, INC.
Environmental & Water-Resource Consultants

Technical Memorandum

Date: September 27, 2006

From: Deborah Hathaway, P.E. and Bryan Grigsby, R.G.

To: Dick Wolfe, P.E., Assistant State Engineer, Colorado Department of Water Resources

Subject: **Responses to Review Comments of Coalbed Methane Stream Depletion Assessment Study, February 2006**

Comments were received as identified below:

⋄ Reviewer A: BP America Production Company: Comments prepared by Wright Water Engineers, June 2006

⋄ Reviewer B: Southern Ute Indian Tribe: Comments provided by letter from Janice Sheftel to Dick Wolfe, June 23, 2006

⋄ Reviewer C: On behalf of unidentified property owners in the outcrop area: Comments provided by letter from James McCord, of Hydrosphere Resource Consultants, to Dick Wolfe, May 3, 2006.

Primary comments and responses are summarized below, with respect to common topic areas, where applicable.

MODELING METHODOLOGY: THE SIMPLICITY OF THE GLOVER METHOD

All three reviewers were critical of the application of the Glover Method, based on their perceptions that due to the method's simplicity, the method results would be erroneous. Interestingly, there was a lack of consensus on the direction of the perceived error. One reviewer, James McCord, representing property owners near the outcrop, stated that the results would underestimate actual stream, spring and groundwater depletion. On the other hand, the BP and Ute reviewers, representing the extraction industry, believed the opposite, that the results by this method would overestimate the actual depletions.

SSP&A disagrees that there is a specific bias towards underestimation or overestimation of depletion using this method. The Glover method is reasonably-well suited to the project goals, as the problem was structured. Regardless of whether an analytical method, such as the Glover method, or a numerical model (for example, as could be constructed using MODFLOW) is applied, calibrating the model using the historic data provides the best means of improving accuracy. In this application, all of the readily available data were employed in obtaining model parameters through a calibration procedure.

The model parameters thus derived and the model results did not differ substantially from those determined in a previous MODFLOW analysis. It does not appear to the investigators that there is reasonable cause to consider the results of this study as either underestimated or overestimated, particularly, as a function of the modeling technique. This is not to say that additional precision could not be obtained in the future, through additional modeling analysis, if significant new data were developed. However, the results from this study should be of sufficient precision to support general analysis of basin conditions and to make associated management decisions or to develop regulatory guidance.

Some reviewers identify specific areas of concern – these are addressed further below.

"The depletion underestimation error relates to problems in their conceptualization and application of the Glover method" (Reviewer C, p. 1). *"In the higher outcrop areas, unconfined drainage likely does not approach the volumes of water needed to attenuate drawdowns to 'appear' as constant heads in nearby portions of the aquifer"* (Reviewer C, p. 3).

One can apply a simplified volumetric analysis to provide some idea of the magnitude of drawdown likely to occur in the outcrop, this being the underlying concern. For example, if one assumes for this purpose that all depletion impacts were expressed as outcrop drawdown (i.e., there were *no* impacts to any streams, and *all* impacts were transmitted only to shallow groundwater in the outcrop area), given the volume of water in unconfined storage in the shallow aquifer, and assuming typical unconfined storage properties, the decline in water levels as a result of CBM water production would be on the order of a half an inch per year. This very minor amount of drawdown is consistent with the assumption made in the modeling analysis that the outcrop will function hydraulically as a "line-source", and with the idealization of the constant-head boundary. In fact, given the small impact at this location, one could alternatively model the system with a no-flow boundary north of the outcrop, with little difference in results. Such an approach was implicit in the MODLFOW analysis, and as noted, there was little difference in the depletions computed in that study. Other than providing an opinion that the outcrop should be treated as a no-flow boundary, Reviewer C offers no evidence that impacts are underestimated.

Reviewer A indicates (p. 4) that the Glover method is conservative, and that a more rigorous Hydrogeologic evaluation would show that the non-tributary line should be located closer to the outcrop. The reviewer expresses no basis for the opinion that the method is biased conservatively, other than noting that data from the Pine River Ranches Study shows that there is *"no hydraulic connection between Fruitland Formation wells completed beneath the Pine River alluvium and Fruitland Formation wells*

located 1 to 1.5 miles to the south". This opinion is not documented specifically; however, we infer that the reviewer is referring to the low pressure changes in observation wells in this area. SSP&A notes that the occurrence of small pressure changes is not unexpected; in our modeling analysis of historic responses, this response was reproduced.

Reviewer A recommends (p.4) that a three-dimensional groundwater model be prepared for those areas to more accurately define the tributary boundary. A three-dimensional groundwater model was prepared by previous investigators under the 3M studies. These models did not differ dramatically with respect to quantifications of stream depletion from those of the present study; therefore, unless significant new data is developed, it is unclear that a new three-dimensional numerical model would substantially improve understanding in this basin as it relates to the broad regulatory goals of this study.

IMPACTS OF DEVELOPMENT ON SEEPS AND SPRINGS, AND ON GROUNDWATER LEVELS IN THE OUTCROP AREA

Reviewer C raises the concern that the impacts of CBM development on the flows of specific seeps and springs in the outcrop area have not been quantified; and, similarly, that impacts on shallow groundwater levels are unidentified. He expresses concern that impacts of CBM pumping may cause seeps and springs to dry up, as well as shallow wells.

An analysis of drawdown impacts using the information developed in the study was made prior to the final public meeting in Durango to address this concern and is briefly described above. Impacts to groundwater levels in the outcrop area are expected to be very small. Impacts of this magnitude will not significantly impact wells. Whether or not a seep or spring would be impacted would depend on the potentiometric head at such locations, and their sensitivity to changes on the order of a few inches. The evaluation of specific impacts at localized sites is beyond the scope of this study. However, the data reviewed for this study, as well as some additional data provided by Reviewer A for the Pinos River drainage near the outcrop (Oldaker, 2005), suggests that there is little change in potentiometric surface in the outcrop area.

REPRESENTATION OF THE OUTCROP AREA AS A "LINE-SOURCE" FEATURE

While agreeing with the designation of the outcrop area as an appropriate "line-source" feature for the Glover analysis with respect to the deep basin analysis, Reviewer C questions the validity of this

approach with respect to tributary streams, seeps and springs. In response, it is noted that the "source" of water in the outcrop area is not only the water available directly in the surface water features, but also, the "water-table storage" of the unconfined system. In the outcrop area, the unconfined storage will be several orders of magnitude greater than that in the confined portion of the formation, deeper within the basin. Water in storage within the outcrop represents a significant "source" in the context of the basin analysis and is therefore modeled in this fashion. The impacts of deep basin pumping to the springs, seeps and outcrop storage are "lumped" in the depletion results. Impacts to water levels in the outcrop area were not quantified in the report; however, from the analyses provided in the report, one may make inferences regarding the drawdown, which is estimated to average less than one foot over a 20 year period at present levels of pumping (see section above).

OCCURRENCE OF VARIABLE PERMEABILITY AND COMPARTMENTALIZATION

Reviewer B (p. 1) notes that permeability in the basin is variable, and that a reduction in permeability as coal is depressurized occurs. He cites these processes as the reason for considering that the method results in an over-estimation of stream depletion. SSP&A would agree that there is variable permeability and some areas of very low permeability. However, the low value of permeability selected for the model is not inconsistent with the presence of relatively low permeability areas or with local compartmentalization. Because the value of permeability used by SSP&A was selected using a modeling procedure wherein historic production data for the entire basin and pressure changes from numerous wells were evaluated, the selected permeability is a reasonable average that represents all of the formation characteristics, including any historic reductions in permeability or formation heterogeneities. On the other hand, in the fairway region, a suitable "calibration" could not be achieved with the available data, and in this area, it was inferred that either the data were insufficient to determine a single value for permeability that would be applicable for the purposes of this study, or, the formation heterogeneity or gas impacts were of a magnitude that interfered with the application of this methodology.

HYDRAULIC CONNECTION BETWEEN THE STREAM AND THE AQUIFER

Reviewer B (p.1) expresses concern that the stream is not fully penetrating the aquifer, and that the stream may have reduced bed permeability. SSP&A defined the "line source" for the Glover analysis as a combination of the streams where they cross the outcrop and the outcrop itself. As such, this source is fully penetrating, as the outcrop (with its storage properties orders of magnitude greater than the areas

of the aquifer wherein production occurs) is in full hydraulic communication with the dipping aquifer. One may debate timing issues between impacts felt at the outcrop and impacts precisely expressed at the physical streams. Some lagging of impacts to the streams from the outcrop impacts will occur, however, these are not anticipated to be of a magnitude that would significantly impact the study's findings. Regarding the potential for a stream bed to have reduced permeability, it is noted that these streams are located close to the mountain front; as such, they are of relatively high gradient and carry significant flows during the run-off season. Streams with these characteristics are unlikely to have significant and persistent accumulations of clay or silt that would prohibit hydraulic communication between the stream and aquifer.

STORAGE VALUES

Reviewer B (p. 2) states:

> "*using the wrong, lower storage values, greatly overestimates stream depletion, especially near the outcrop*".

The reviewer misunderstands SSP&A's method. The reviewer is critical in that the Glover method did not employ image wells as were used in the Theis analysis from which parameters were derived. The use of the image wells in the Theis analysis were for the purpose of providing consistency among the two methods, because the Glover solution implicitly assumes a constant-head boundary, and it is only by using the image wells in the Theis solution that one can obtain a similar conceptualization. Because the Glover solution already incorporates the constant-head boundary, there would be no need to use image wells in this case exactly as would be simulated is premised on the existence of conditions. Thus, the Glover method used the same storage values as were used for the historic calibration analysis. The reviewer also misunderstands the rationale for using the confined storage in the analysis. The confined, or lower, storage value is representative of the vast basin area through which impacts are propagated to the streams and outcrop. This is the correct value for use in the analysis.

Reviewer A (p. 6, 7) suggests that the use of an unconfined storage coefficient might be a better approximation to aquifer conditions, and that with such an assumption, the non-tributary line would shift towards the outcrop. SSP&A notes that the use of an unconfined storage coefficient for this basin would be inconsistent with the hydrogeologic conditions as reflected in pressure and geologic data; the effect of such a substitution would be to move the non-tributary line towards the outcrop unjustifiably. Only in the

immediate outcrop area would an unconfined storage value be appropriate. The structuring of the problem as was done in the report provides a "lumped" depletion, impacting the streams and outcrop storage together. To the extent that impacts from the outcrop to the stream are lagged, the computed impact will not precisely represent the impact on the stream. Regardless, the present study method provides a good sense of the general magnitude of impacts with potential to affect streams, in accordance with the goals of the study.

RECHARGE AND DEPLETION

Reviewer B (p.3) notes that under some scenarios depletion may exceed 500 acre feet per year, but that recharge to the Fruitland Formation has been estimated (by AHA, 2000) as about 200 acre feet per year. For an unidentified reason, this reviewer considers that this situation "pushes the envelope". First, it is noted that recharge is difficult to estimate, and that SSP&A has not determined in this study whether or not the AHA recharge estimate is reasonable. Second, it is noted that the AHA estimate relates to an amount of discharge to rivers crossing the outcrop. But more importantly, SSP&A notes that no rationale exists that would render depletion problematic if it exceeds the baseline outcrop discharge to streams. Depletion is simply a reduction in net stream gains/losses due to a specific event. This may represent a reduction in gains, or, increase in losses, or some combination, depending on the stream elevation as compared to the aquifer head. However, in that there is significantly more than 200 or 500 acre feet flowing in the rivers, the flow in the rivers is more than sufficient to be impacted on the order of a few hundred acre feet (less than 1 cfs) per year.

THE EXCLUSION OF THE FAIRWAY AREA

Reviewer A suggests that the Fairway area not be excluded from analysis. SSP&A notes that the methodology for this study was not appropriate for the Fairway area.

LITERATURE ON SHORTCOMINGS OF THE GLOVER METHOD

Reviewer B (p. 3) provides a reference that addresses shortcomings in the Glover Method. SSP&A has reviewed extensive literature on this topic and understands limitations of the Glover Method and other methods, including numerical models. All modeling methods have limitations, both in computational or solution schemes, and in their ability to represent data fields. The shortcomings of the

Glover Method, and how these were handled in this analysis, were discussed in Section 6.2.2 and in Section 8 of the report.

Reviewer A (p. 5) provides references to several sources in the literature on the shortcomings of the Glover Method. Beyond the general comment noted immediately above, the reviewer is referred to the discussion on hydraulic communication: in this physiographic setting with reasonably high gradient streams actively draining mountainous areas, there is no reason to believe that restrictive stream bed conductivities are present, especially as compared to the already very low permeability assumed in the analysis.

EVALUATION OF ISOTOPIC DATA RELATED TO GROUNDWATER AGE

Reviewer A provides some additional information regarding age dating of the groundwater. The reviewer then argues that groundwater age dating is reason to infer that there is no connection between surface waters and groundwater deep in the Fruitland formation. For purposes of this study, SSP&A is not concerned with the specific source or timing of groundwater in the deep basin. Rather, of importance to this study is the potential for transmission of a "pressure effect", as would be reflected by pressure changes in response to production histories. In the SSP&A report, the CGS provided some discussion of groundwater ages, primarily for background purposes. Regarding the specific comments on groundwater ages (p. 11), Reviewer A is correct, the discrepancy is due to the maximum measurable age for Cl (which is in the neighborhood of 2 million yrs).

SPECIFIC RESPONSES TO DETAILED COMMENTS

Reviewer A provided additional detailed comments (p. 11-16). Where these have not yet been addressed with the responses above, and where clarification is deemed useful, additional clarification is provided below, according to the numbered comments.

1.   The reviewer objects to a phrase in a sentence within a general introductory paragraph. This sentence relates the nature of public concerns in the basin, which include the phrase cited. The following sentence explains which of the concerns are or are not addressed in the study. As part of general background material, the sentence is informative.

2.   Modeling assumptions are adequately described in the body of the text; inclusion of these in the Executive Summary is beyond the intended level of detail for this summary. SSP&A does not share the reviewer's position that the model results are "worst case" estimates.

3.   The statement clearly states that modeling is the basis for the quantified depletion. The reviewer's concern that this could be confused with an observation or a measurement is unwarranted.

4.   The cited report, CGS Open-File Report 01-4 by Kirkham and Navarre, was not included in the summary of geologic conditions due to the generalized scope of the overview task. The Colorado Geologic Survey and SSP&A acknowledge this publication and its contribution to geologic knowledge of the basin. The information provided in the report is not considered to impact interpretation of the general nature of flow within the basin.

5.   The study does not aim to evaluate localized groundwater elevation changes at specific sites; this is beyond the scope of the study, which focused on characterization of depletion impacts. However, where pressure data were available to the study team to use for model calibration, these data were incorporated into a PEST analysis to obtain a set of hydraulic parameters for the stream depletion analysis.

7.   Down-hole video provided by Reviewer A shows calcite in numerous fractures. The occurrence of calcite healing and sealing of fractures is not debated; however, a full discussion of fracture types and conditions is beyond the scope of this report. The presence of a large number of sealed fractures is not at all inconsistent with the hydraulic properties derived for the formation. The assumed transmissivity of 1 ft^2/day, which would relate to a permeability of about 4 to 20 md, is a *very* low value and reflects a considerable amount of resistance to flow and pressure impacts.

8.   Data in various locations were examined to address the hydraulic response of the formations to the pumping history. This exercise, described in Section 5.3, provides the basis for the handling of aquifer conditions. The result of this work resulted in the assignment of very low permeability to the CBM-related formation. This is the key feature of the analysis, not whether one chooses to describe this as "through-flowing" or "compartmentalized".

9.   SSP&A disagrees that this is a worst-case assumption. The statement is supported by the analysis of many years of production data and formation response.

10.   The Pictured Cliffs Sandstone is considered to be part of the aquifer; therefore, the statement that the Fruitland Formation non-coal strata permeability is very low is valid. The statement does not imply anything about the Pictured Cliffs Sandstone permeability.

11.   In evaluating changes in potentiometric heads in the basin over time, the maps of Berry and McCord were reviewed. The Kaiser et al. (1994) map was chosen for use in the report (Figure 5.2) because it both includes more data points than the two other maps and is still illustrative of conditions in the basin prior to significant CBM production. More importantly, comparisons between Figures 5.2 and 5.6 allow transient pressure changes from existing wells in response to CBM production to be examined.

12.   The reviewer correctly notes that the cited figure should be Figure 5.6.

13.   The reviewer misunderstands the analysis. SSP&A stated that evaluation of site-specific impacts is not the goal of the study. That being given as a restriction on study goals, it is not to say that where long-term pressure data are available, they wouldn't be utilized to assist in characterizing basin conditions.

16.   The statement made here is based solely on the noted observations; this is not inconsistent with the results of the hydraulic analysis described in report Section 5.

17.   Noted; this appears to be a typographical error.

18.   The presence of water at substantially different water ages may be of interest in identifying their source and flow paths. Regardless, what is of prime importance to this study is the propagation of a pressure impact hydraulically, not the age-dating of waters. Evidence was not encountered that suggested that regionally extensive barriers to the transmission of a hydraulic impact were present.

19.   The Fruitland-Pictured Cliffs hydrostratigraphic unit would not be termed an "aquifer" when compared to many units in the Rocky Mountain region due to its very low permeability. Regardless, in the context of this study where its permeability is much greater than that of the surrounding formations, it is conceptualized as the primary unit through which a pressure impact will propagate. In a relative sense, it is the conceptual "aquifer" for the basin. However, SSP&A agrees with the reviewer in that in many respects, given the low permeability, flow in this formation is severely restricted. The formation was modeled with the very low value of permeability supported by the historic data.

20.   Discussed in general comments above.

22.   This has not been calculated, however, the model has been made available to those wishing to apply it to other questions such as this.

23.   The basis for this opinion requires explanation; that an "obvious exception" exists is unclear.

General comment regarding figure titles: All of the figures are titled in the original document and its pdf file. Titles are as reflected in the Table of Contents, p iv. A downloading or software problem is suspected.   However, these are provided below for further reference, along with the requested information regarding source material for the CGS figures.

24.   Figure 2.1: Outcrop is a compilation from published geologic maps – Carroll et al., 1997; Carroll et al., 1998; Carroll et al., 1999; Carroll and Tremain-Ambrose, 1998; Steven et al., 1974; Wray, 2000. Precipitation information comes from CGS GIS data set used in the Ground Water Atlas of Colorado (Topper et al., 2003)

25.   Figure 2.2: Outcrop is a compilation from published geologic maps – Carroll et al., 1997; Carroll et al., 1998; Carroll et al., 1999; Carroll and Tremain-Ambrose, 1998; Steven et al., 1974; Wray, 2000. The drainage basin divides were determined by CGS for this figure.

26.   Figure 3.1: Paleogeography by Ron Blakey,
       http://jan.ucc.nau.edu/~rcb7/crepaleo.html

27.   Figure 3.3: Outcrops are a compilation from published geologic maps – Carroll et al., 1997; Carroll et al., 1998; Carroll et al., 1999; Carroll and Tremain-Ambrose, 1998; Steven et al., 1974; Wray, 2000.

28.   Figure 3.5: Reference used was Ayers et al., 1994 (originally from Ayers and Ambrose, 1990).

29 and 30. Figures 3.6 and 3.7: Compiled by CGS from Condon, 1997; Tremain et al., 1994; and from geologic maps Carroll et al., 1997; Carroll et al., 1998; Carroll et al., 1999.

34.   Figure 5.5: Logic behind comment is unclear. The report does not state that downbasin production is draining the Fruitland Formation. SSP&A calculated an extremely small impact to the outcrop and stream areas; these impacts do not imply that springs would be greatly

diminished or nonexistent. It should be noted that the springs shown are those provided in the two publications referenced on the figure. The Colorado Geologic Survey has not evaluated the springs to determine their actual nature and whether they represent flow from the Fruitland-Pictured Cliffs aquifer or drainage from shallow upslope unconfined materials.

36.   Table 3.2: Pine River Ranches 1 is a measured section from Wray, 2000.

REVIEW COMMENTS REGARDING THE REPORT:

"COALBED METHANE STREAM DEPLETION ASSESSMENT STUDY NORTHERN SAN JUAN BASIN, COLORADO"

BY S.S. PAPADOPULOS & ASSOCIATES, INC. FEBRUARY 2006

For:

BP AMERICA PRODUCTION COMPANY DENVER, CO

WWE

Wright Water Engineers, Inc.

June 2006

001-015.020

REVIEW COMMENTS REGARDING THE REPORT:

"COALBED METHANE STREAM DEPLETION ASSESSMENT STUDY NORTHERN SAN JUAN BASIN, COLORADO"

BY S.S. PAPADOPULOS & ASSOCIATES, INC. FEBRUARY 2006

For:

BP AMERICA PRODUCTION COMPANY DENVER, CO

JUNE 2006
001-015.020

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REVIEW COMMENTS
REGARDING PAPADOPULOS REPORT

1.0   INTRODUCTION

Wright Water Engineers, Inc. (WWE),[1] and six outside reviewers[2], were asked by BP America Production Company (BP) to review and comment on a February 2006 report entitled "Coalbed Methane Stream Depletion Assessment Study—Northern San Juan Basin, Colorado" (Study). This Study was a joint effort by the Colorado Oil and Gas Conservation Commission (COGCC), the Colorado Geological Survey (CGS) and the Colorado State Engineer's Office, Division of Water Resources (DWR); all agencies are within the Colorado Department of Natural Resources (DNR).   The request by BP was in response to an April 4, 2006 letter from the DWR to the general public for review and comments regarding this Study.   This report summarizes our review and comments.

2.0   GENERAL OVERVIEW OF THE STUDY

S.S. Papadopulos and Associates, Inc. (Papadopulos) was awarded a contract to develop a quantitative assessment of the levels of stream depletion or reduction in formation outflows in the Northern San Juan Basin that may be occurring as a result of the removal of water by coalbed methane (CBM) extraction via wells.   According to the DNR's July 2005 document entitled "Coalbed Methane Stream Depletion Assessment Study—Scope of Work" (scoping document), the co-sponsors of the Study were asked to develop:

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[1] Wright Water Engineers, Inc. staff who prepared this review are Gary Witt, P.G. and Jonathan Jones, P.E., with assistance from Peter Foster, P.E. and Alissa Krochenski.

[2] WWE requested independent review by the following people: John Rold, C.P.G. (previously Colorado State Geologist and currently consultant), Robert Kirkham, P.G. (past employee of the Colorado Geological Survey, where he conducted geologic surveys in the San Juan Basin and currently consultant), Professor Ray Kenny, Ph.D. (Assistant Dean, Natural and Behavioral Sciences, Ft. Lewis College in Durango), Phillippe Martin, C.P.G. (president of Martin and Wood and expert on groundwater modeling), Paul Oldaker, Hydrogeologist (consultant with over 25 years of experience in the San Juan Basin), Eric Bikis, P.G. (managing partner of Bikis Water Consultants with extensive local hydrologic experience).

- A reliable assessment of the levels of depletions,

- Definition of the areas that might be classified as nontributary where CBM development is ongoing,

- Definition of potential correlations of water quality, geology, aquifer geometry, or formation/well depth that could lead to general guidelines about the potential for stream depletion and that would be useful in either prompting or avoiding more detailed studies, and

- Recommendations for further data collection or investigation.

The resulting 56-page Study by Papadopulos (February 2006) includes a three-page Executive Summary, 27 figures, four tables and four appendices. The document was made available for comment via an April 4, 2006 letter from DWR to the general public.

In general, the Study authors and DWR summarized their results as follows:

1. The magnitude of the stream depletions associated with current and future CBM development from all wells is small (155 and 170 acre-feet per year [AF/yr], respectively, assuming no infill wells are allowed within 1.5 miles of the outcrop) when distributed across the three major drainage basins (Animas-Florida, Los Pinos [Pine], Piedra-San Juan) that comprise the Northern San Juan Basin in Colorado.

2. Less than 50 AF/yr (or one-third) of these stream depletions are considered to occur out-of-priority (i.e., at times when senior water users would be injured). The remaining amount will occur when there are not senior calls on the rivers.

3. The magnitude of the stream depletions from CBM wells is small as compared to the depletions associated with an equivalent number of exempt domestic wells (600 AF/yr) or the 2,670 exempt domestic wells if developed on each 160-acre tract (1,600 AF/yr). In addition, each CBM well is considered to have a life expectancy of approximately 20 years, while an exempt domestic well can have a production life that is potentially perpetual.

4. While admittedly developed for unconfined conditions, the Glover-Balmer method can be used as a "first order indicator of general conditions" to assess the magnitude of stream depletions and to conservatively identify the horizontal distance from the outcrop (stream) where groundwater resources meet the nontributary statutory definition.

5. The statutory definition of nontributary groundwater is conservatively identified as 10.5 miles from the outcrop of the Fruitland-Pictured Cliffs Formation.

3.0 SUMMARY OF WWE COMMENTS AND CONCLUSIONS

The Study is well written and organized, and contains considerable background data and information. Papadopulos is certainly well-qualified to conduct the work, and their staff members (as well as DNR staff) were responsive to our inquiries. For example, WWE received copies of the Glover-Balmer analysis (conducted by Papadopulos) for review. It appears that nearly all of the subject areas outlined in the scoping document were addressed to varying levels of detail; some exceptions are discussed later in this report.

Conclusions that WWE and our reviewers draw from this Study include:

1. The total estimated depletion of 155 AF/yr is 0.07 percent of the combined average annual flow (227,000 AF/yr) of the three main rivers in the basin (Animas, Florida, and Pine rivers) potentially affected by the CBM production. This is the equivalent of 0.21 cubic feet per second (cfs) or 91 gallons per minute (gpm), which is orders of magnitude below the natural annual flow variation and far less than the accuracy of standard streamflow measurements.

2. Consideration of these depletions on a well-specific basis suggests an average depletion of approximately 0.16 AF/yr or 0.1 gpm per well assuming approximately 1,000 CBM wells within 10.5 miles of the outcrop as cited by DWR in their cover letter for the Study. This is considerably less than the flow of a typical garden hose (6 to 10 gpm per the American Water Works Association, 1975) and the assumed 0.6 AF/yr appropriation allotted individual domestic

exempt well owners for which there is no augmentation requirement as outlined in the April 4, 2006 letter from DWR.

3.   The conservatism of the Glover-Balmer method suggests that groundwater located greater than 10.5 miles from the Pictured Cliffs Sandstone outcrop is nontributary and unlikely to be refuted by further analysis. Existing site-specific data and a more rigorous hydrogeologic evaluation using numerical or analytical methods will show that the nontributary line is much closer to the outcrop than indicated by this Study. For example, the existing Pine River Ranches Study described below already shows there is no observed hydraulic connection between Fruitland Formation wells completed beneath the Pine River alluvium (i.e., in the Fruitland Formation subcrop) and Fruitland Formation wells located 1.0 to 1.5 miles to the south.

In summary, WWE recommends that DNR clearly define this Study for what it is: "a first order indicator of general conditions," using an extremely conservative analytical tool. The Study should also state that the boundary between tributary and nontributary groundwater is conservative and that the areas not identified in the Study as nontributary are subject to modification with more rigorous and sophisticated analysis, properly calibrated to reflect available data. WWE recommends that a three-dimensional groundwater model be prepared for those areas to more accurately define this boundary.

4.0   GENERAL WWE REVIEW COMMENTS

This section provides general comments regarding the Study. Detailed (page-specific) comments are addressed in the next section.

4.1   Applicability of Glover-Balmer Method

The scoping document for the Study states that the determination of depletions will be by the analytical "Glover" (Glover-Balmer) method. WWE's outside reviewers of the Study have noted that the use of the Glover-Balmer Stream Depletion Model in this application is not

consistent with the various conditions originally cited by Glover-Balmer (1954) for its use, including:

- Stream fully penetrates the aquifer.

- Aquifer is homogeneous and isotropic.

- Aquifer is unconfined.

- Aquifer has a non-sloping water table.

- Flow in the aquifer is horizontal and dominated by one phase.

- All water pumped from the aquifer system comes solely from the stream (not another source).

- Aquifer has direct hydraulic connection with the stream.

Papadopulos makes a commendable effort to justify conformance with these conditions so that the use of the model can be validated. However, many of the assumptions have not been adequately justified.

Professor Ray Kenny (one of WWE's reviewers) referred WWE to three published articles by McCurry (2004), Sophocleous et al. (1995), and Miller and Durnford (2005) that evaluate the Glover analytical model assumptions for the prediction of stream depletions. McCurry concludes that the degree to which the stream is fully penetrating and hydraulically connected to the aquifer is the most significant factor relative to the accuracy of the estimated stream bed depletions. Sophocleous et al. states that the streambed conductivity (i.e., hydraulic connection with the stream) and partial stream penetration affect the accuracy of the Glover method more than aquifer heterogeneity. Miller and Durnford are currently investigating (or recently completed investigation of) errors associated with heterogeneous aquifers and non-ideal conditions. WWE suggests that Papadopulos include a brief discussion of these and similar articles, including their results, conclusions, and implications to the Study.

The use of the Glover-Balmer stream depletion method has been sanctioned by DNR in other settings, particularly in cases involving the identification of nontributary groundwater. The SEO's justification for its use has been that the method is conservative and tends to over-estimate the stream depletions. Assuming that this approach is only a "first-order determination of depletions" as stated by Papadopulos, a supportable conclusion from this Study is that the location of the nontributary/tributary demarcation line is no more than 10.5 miles from the outcrop and would be much closer to the outcrop if analyzed using a method better suited and more closely calibrated to these site-specific conditions.

WWE and many of our reviewers are aware of, or were active participants in, a debate during the 1980s involving the use of the Glover-Balmer method as a means to determine the nontributary groundwater line within the Denver Basin. Its use was rejected in favor of a more sophisticated numeric model that could be constructed to account for the heterogeneities of the aquifer systems to be modeled.

A comparison of the Denver and San Juan basins provides an opportunity to assess the reasonableness of the nontributary groundwater line identified in the study. Within the Denver Basin, hydraulic conductivities are higher than the San Juan Basin, suggesting withdrawal of groundwater will influence a larger area. Consequently, this should result in a nontributary line in the Denver Basin that is greater than 10.5 miles from the Denver Basin outcrop. This is not the case. In general, the nontributary line along the western edge of the Denver Basin (where the upturned geologic units most closely mimic those of the San Juan Basin) is within a few miles of the outcrop. The principal reason for this is the use of a storativity value characteristic of unconfined conditions within the Denver Basin numeric model. Unconfined conditions indicate that there is a considerable amount of water in storage within the formation that can be provided to the well in lieu of active withdrawal from a nearby stream. This results in both a smaller effect on the streams and a nontributary line that is closer to the outcrop. Within the San Juan Basin, Papadopulos assumed a confined storage coefficient that represents limited water in storage within the formation, thus forcing pressure reduction to be felt at greater distances. While the assumed confined values may be representative of the formations at considerable distance from the outcrop, these values are likely too small for areas closer to the outcrop.

Furthermore, it is known that as aquifers are dewatered and approach atmospheric conditions, the apparent storage coefficient increases and may ultimately reflect a value closer to unconfined conditions. An increase in the apparent storage coefficient will reduce the distance from the outcrop to the nontributary line.

WWE conducted a sensitivity analysis of the Glover-Balmer method by varying storage coefficients to define the location of the nontributary line (see Table 1). These data confirm the location of the nontributary line at 10.5 miles from the outcrop under the conditions assumed by Papadopulos in their Study. As shown in Table 1, changes to the storage coefficient that are consistent with other basins in Colorado result in considerably smaller distances from the outcrop to the nontributary line using the same Glover-Balmer method. For example, Table 1 shows that the use of a storage coefficient similar to the Laramie-Fox Hills Sandstone within the Denver Basin (S = 0.15) results in a nontributary line that is approximately 0.5 miles from the outcrop in the San Juan Basin. Based on existing data and information, a storage coefficient closer to 0.15 appears to be more supportable and applicable to the San Juan Basin, especially in the vicinity of the outcrop, than the value adopted by Papadopulos. This is an example of the highly conservative and generalized nature of the Papadopulos analysis, which leads to an overestimate of the tributary area. WWE recommends that the Study should include a sensitivity analysis to emphasize the conservative nature of the adopted storage coefficient and resulting conclusions.

Table 1
Glover-Balmer Method Sensitivity Analysis

Distance from Outcrop (ft)	Distance from Outcrop (miles)	Transmissivity (ft²/day)	Transmissivity (gpd/ft)	Storage Coefficient (unitless)	Depletion % at 100 years	Meets NT* Definition? Y/N
54,912	10.4	1.2	9.0	0.00031	0.106	N
55,440	10.5	1.2	9.0	0.00031	0.094	Y
30,700	5.81	1.2	9.0	0.001	0.101	N
30,750	5.82	1.2	9.0	0.001	0.099	Y
9,700	1.84	1.2	9.0	0.01	0.102	N
9,700	1.84	1.2	9.0	0.01	0.095	Y
2,500	0.47	1.2	9.0	0.15	0.104	N
2,550	0.48	1.2	9.0	0.15	0.082	Y

*NT = Nontributary

4.2 Comparisons to Existing Field Data and Previous Studies

Papadopulos cites numerous references and data sources for the Study. One of those referenced documents is the ongoing data collection and analyses being conducted by Paul Oldaker for BP (referenced in the Study as "Oldaker, P. 2005"). This investigation is especially relevant in that it represents 12 years of data from numerous wells completed in the Fruitland Formation at or near the outcrop in the Pine River drainage. These data show that those wells completed in the Fruitland Formation below the Pine River alluvium have potentiometric elevations above the corresponding Pine River water surface elevations and have not shown evidence of decline due to downbasin gas and water production during the 12 years of observation. This potentiometric surface indicates that an upward groundwater gradient exists from the Fruitland Formation to the Pine River. Therefore, stream losses (depletions) cannot occur at this location. Conversely, other Fruitland Formation wells located downdip from the outcrop do show potentiometric head declines. These data suggest that the Fruitland Formation is not hydraulically connected from the center of the basin to the outcrop. This is further supported by analyzing gas discharge rates from seeps in the Pine River Ranches area; these have a much better correlation with precipitation than with gas production and downbasin potentiometric head changes. The

significance of these data is so compelling that we have included this information (a two CD set) as an attachment to the hard copy version of this report.

The Fairway is cited by Papadopulos as an area where gas saturation is higher and water saturation is lower, suggesting that a one-phase flow model may not be suitable for modeling pressure changes in this region (i.e., violating the assumptions used in the Theis and Glover-Balmer analyses). As stated in Appendix B of the Study, "If pressure changes are primarily due to pumping of gas, water pumping data alone is not sufficient input to the Theis model." As a result, Papadopulos elected to remove this area from the Study for purposes of delineating the tributary/nontributary line. However, since the Study is an extremely conservative first order indicator of general conditions, and the remaining area in the basin also includes aspects of these two-phase effects, WWE suggests that the Fairway area should not be excluded. WWE also observes that the specific characteristics of the Fairway area could be better represented by a three-dimensional groundwater model, calibrated with data from that area.

Another reference frequently made by Papadopulos in the Study is to a publication by Snyder et al. (2003) and Riese et al. (2005). These publications include substantial general and isotopic chemical data that have been used to assess the source and age of the water produced during gas exploration and development within the San Juan Basin.

According to the Study, the ionic chemistry data suggest multiple sources for the produced waters but the complexity of the basin precludes the use of major ions to determine sources within the Fruitland Formation. As a result, isotope chemical analysis was undertaken to identify possible sources for this produced water. From these analyses, at least four possible sources were identified. Papadopulos recognizes this complexity by acknowledging that these isotopic signatures suggest local compartmentalization (i.e., site-specific hydrogeologic conditions). To evaluate the subject of age-dating, WWE has prepared the following background text, which is shown in italics.

Defining Groundwater Age

The "age" of groundwater is generally considered to be the amount of time that has elapsed since the water was last in contact with the atmosphere, i.e., its residence time in the subsurface.

The age of groundwater is determined by examining chemical and isotope tracers in the groundwater that change their properties in a predictable way with time. All such properties must have a known value at the time of water entry to the subsurface (aquifer recharge); the measured value at the time of sampling is then an indicator of the elapsed time between the recharge and sampling times.

Certain tracers are more suitable for different age ranges. For young groundwaters, the most common dating method is one that measures the relative abundances of tritium (^3H) and helium-3 (^3He). Tritium is a radioactive isotope of hydrogen that decays to ^3He with a half-life of 12.4 years.

Another well-known dating method for older groundwater uses carbon-14 (^{14}C) dissolved in the water. ^{14}C is formed in the upper atmosphere as a result of cosmic ray bombardment. The ^{14}C is incorporated into carbon dioxide and becomes distributed throughout the atmosphere. Carbon dioxide containing ^{14}C ($^{14}CO_2$) is a small fraction (about 10^{-12}) of the total atmospheric CO_2. $^{14}CO_2$ dissolves into the oceans and surface freshwaters and becomes part of the normal hydrological cycle. Once dissolved, $^{14}CO_2$ enters the subsurface in groundwater and becomes isolated from the atmosphere (it ceases being replenished from the atmosphere). The normal radioactive decay of ^{14}C then becomes a clock indicating the subsurface residence time of a groundwater sample. ^{14}C decays with a half-life of 5,730 years, providing a useful dating method for groundwaters up to about 40,000 years old. Having said this, it is important to recognize that the use of ^{14}C is invalid for water-bearing units containing carbon (i.e., coal, oil, gas, etc.) because of the age of the carbon and its influence as a large reservoir of contamination.

The long-lived radionuclides, chlorine-36 (^{36}Cl, half-life = 301,000 years) and iodine-129 (^{129}I, half-life = 17,000,000 years) are also used to study groundwater flow systems. Like ^{14}C and ^3H, both ^{36}Cl and ^{129}I are produced in the upper atmosphere by cosmic ray bombardment and become part of the hydrological cycle dissolved in precipitation. Their long half-lives make them suitable for measuring very old (millions of years) groundwaters. Helium-4 (^4H) is another useful radionuclide for age-dating. However, ^{36}Cl, ^{129}I, ^3H, and ^4H are also generated in the subsurface via the decay of uranium. As a result, care must be exercised in evaluating such results so as to draw appropriate conclusions from both the individual and comparative results.

With this as a background, WWE respectfully suggests that Papadopulos should review and potentially revise its section on age dating, because its relevance is incorrectly characterized by Papadopulos as "having too many discrepancies… to use… in a stand alone manner." The apparent "discrepancies" appear to stem from a misunderstanding of the age data published by Riese for different isotopes. For example, Papadopulos cites a discrepancy between an ^{129}I age of 57.0 million years (Ma) and a corresponding ^{36}Cl age of 2.4 Ma. What appears to be misunderstood is that the cited ages represent the minimum age of the sample and not the absolute age. The ^{36}Cl age represents the maximum age of the range for which this isotope can be used. The sample result indicates an age of at least 2.4 Ma. The ^{129}I analysis (capable of analyzing ages to about 80 Ma) was therefore used to determine how much older than 2.4 Ma the sample represented.

In summary, the Riese and Snyder studies indicate that the majority of Fruitland Formation groundwater is tens of millions years old with no connection to the surface waters in the region. The Study should be revised to more accurately present these findings and the supporting data.

5.0   DETAILED COMMENTS

The following is detailed list of comments.

1.   Page ES-1, 1st Paragraph, 3rd Sentence – The comment regarding "how the production of water may be affecting CBM gas seepage at the surface" is not addressed in the report nor is it a stated objective. This should be removed.

2.   Page ES-2, 2nd Paragraph, 2nd Sentence – The major assumption of the modeling is that there is a hydraulic connection between the Fruitland subcrop and downbasin production. This major assumption should be described in the summary. This is a valid and verifiable assumption for determining worst case conditions. It should be stated as such.

3.   Page ES-2, 2nd Paragraph, 2nd Sentence states: "According to the modeling, the depletion as of August 2005 for the CBM wells within the basin in Colorado was

determined to be about 155 AF/yr." This sentence appears to state observed or measured facts. The word "estimated" should be inserted in front of "depletion" since this volume of water was neither measured nor observed.

4.   Section 3.0 (in general) – Reference to geologic mapping along the outcrop belt of the Fruitland Formation and Pictured Cliffs Sandstone occurs in several places. These references do not cite the geologic map of the Basin Mountain Quadrangle (CGS Open-File Report 01-4 by Kirkham and Navarre). This publication includes considerable information on fractures within the Pictured Cliffs Sandstone and cleats within the Fruitland Formation. Of particular interest might be the 10 to 30° difference in orientations between the "face-cleats" of the Fruitland Formation and the fractures within the Pictured Cliffs Sandstone.

5.   Page 3, 3rd Paragraph, 5th Bullet – This is apparently true given the lack of discussion about the observations at the Pine River Ranches study area (see above), but it appears that the parameter estimation analysis did look specifically at localized groundwater elevation changes at specific sites as a means to calibrate the analysis.

6.   Page 9, 2nd Paragraph, Last Sentence – This sentence should include the Paleocene Nacimiento Formation as one of the formations deposited during the Laramide Orogeny.

7.   Page 13, 2nd Paragraph, Fracturing – There is no mention that calcite fills a majority of fractures in the San Juan Basin, as shown by the down-hole videos. Calcite healing and sealing of fractures should be discussed.

8.   Page 26, Section 5.2.2, Compartmentalized Aquifer Conceptual Model – The Pine River Ranches report should be included in this discussion.

9. Page 27, 2nd Bullet, "… there is hydraulic connection…" – Again this is a worst case assumption, not a statement of fact and should be stated as such.

10. Page 28, 3rd Paragraph, Last Sentence – Further explanation and justification should be provided for why the permeability of the Pictured Cliffs Sandstone is not considered significant. Particularly given that this formation was one of the original "pay zones" in many of the original gas wells in the basin.

11. Page 33, 3rd Paragraph, Section 5.3.6, Water Level Conditions – Berry, Oldaker, and McCord all presented potentiometric head maps that should also be referenced.

12. Page 34, 1st Line – Reference is made to Figure 5.7, but we were unable to find this figure. It would seem that the reference should be to Figure 5.6.

13. Page 34, 2nd Paragraph, Last Sentence – If site-specific data were not evaluated, how can it be stated that "pressure trends reflect connection to the saturated unconfined aquifer at the outcrop?" This should again be stated as a worst case assumption.

14. Page 36, 3rd Paragraph, Section 5.4.2, Isotope Chemistry – This section should be titled "Stable Isotope Chemistry" since radiogenic isotopes are discussed in the next section.

15. Page 36, 3rd Paragraph, Last Sentence – Chlorine-36 and iodine-129 are radiogenic isotopes and should be discussed in the next section.

16. Page 37, Carry-over sentence from Page 36 states "…it appears that the aquifer does behave as a single system, at least within several miles of the outcrop." This sentence is somewhat contradictory with the assumption of hydraulic continuity throughout the basin and a tributary distance to the outcrop of 10.5 miles.

17. Page 38, 1st Paragraph, Last Sentence – the sentence should include ^{129}I rather than ^{139}I.

18. Page 38, 2nd Paragraph, Last Sentence – Given the discussion of isotopic age dating provided above, it would seem that substantially different water ages at various geographic locations throughout the basin may suggest a conclusion contrary to this summarizing sentence.

19. Page 41, Last Paragraph (and elsewhere) – reference to the Fruitland-Pictured Cliffs hydrostratigraphic unit as an aquifer is misleading given its reported permeability of 0.01 to 0.1 darcy. This would be considered a barrier to flow in many basins in the Rocky Mountain region.

20. Page 44, 1st Full Paragraph – This paragraph seems to provide justification for concluding that the assumptions used by Papadopulos in their use of the Glover-Balmer method forces the timing of depletions to the streams to be equivalent to the timing of depletions at the outcrop (i.e., is overly conservative in that there is additional travel time from the outcrop to the stream). This is significant in that the statutory definition of nontributary groundwater is time specific. If the timing of the depletions calculated in this manner are "shifted forward in time… on the order of months to a few years" according to the Study text, the location of the nontributary line can arguably be moved toward the outcrop accordingly.

21. Page 44, Last Paragraph, 2nd Sentence – An obvious exception to this is the Pine River Ranches data, which should be noted.

22. Page 45, 1st Full Paragraph, 2nd Sentence – If all wells pumping within the San Juan Basin in Colorado create a depletion of 156 AF/yr, what is the combined effect from the nontributary wells and what is the resulting depletive effect from the tributary wells only?

23.   Page 50, 3rd Paragraph, Last Sentence – An obvious exception to this is the Pine River Ranches data, which should be noted.

24.   Figure 2.1 – Untitled with no source reference.

25.   Figure 2.2 – Untitled with no source reference.

26.   Figure 3.1 – The source of this information should be cited.

27.   Figure 3.3 – Untitled with no source reference.

28.   Figure 3.5 – The source of this information should be cited.

29.   Figure 3.6 – Untitled with no source reference.

30.   Figure 3.7 – Untitled with no source reference.

31.   Figure 3.8 – No figure number.

32.   Figure 5.1 – The general location of this cross section (and others) should be provided on one of the planimetric maps.

33.   Figure 5.2 – Untitled.

34.   Figure 5.5 – If one assumes that downbasin production is draining the Fruitland Formation, then spring flows at the highest elevations of the outcrop should be greatly diminished or nonexistent. Perhaps the existence of these springs (as indicated on this figure) is an indication of a lack of downbasin connectivity.

35.   Figure 6.2 – This is one of the very few plan views of the basin that includes Township and Range numbers. Inclusion of this information on each figure would help to orient the reader (particularly Figure 6.1).

36.   Table 3.2 – The Pine River Ranches 1 well does not exist. WWE is unclear which well is being referenced. Reference to a well with only four seams and 15 feet of coal does not match with any of the ongoing monitoring wells at Pine River Ranches.

37.   Table 5.1 – The Gurr well is part of the Pine River Ranches study area and data from this well were included in this table. However, there are seven other Fruitland and Transition zone wells at Pine River Ranches which are not included. It should be noted that the Gurr well potentiometric head has not responded to any infilling production and is now flattening out.

6.0   REFERENCES

American Water Works Association. 1975. *Sizing Water Service Lines and Meters. AWWA Manual M 22.* Denver, CO: AWWA.

McCurry, G., 2004. Comparing methods of estimating stream depletions due to pumping. *Southwest Hydrology*, Pgs. 6 and 31.

Miller, C.D. and Durnford, D.S., 2005. Modified use of the "SDF" Semi-Analytical Stream Depletion Model in bounded alluvial aquifers. Hydrology Days 2005, Colorado State University, Fort Collins, Colorado, Pgs. 146-159.

Sophocleous, M., Koussis, A., Martin, J.L. and Perkins, S.P., 1995. Evaluation of simplified stream-aquifer depletion models for water rights administration. *Ground Water*, Volume 33, No. 4, Pgs. 579-588.

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September 27, 2006

Dick Wolfe, P.E.
Office of the State Engineer
Division of Water Resources
1313 Sherman Street, Room 818
Denver, CO 80203
VIA E-MAIL: dick.wolfe@dwr.state.co.us

> Re: *Coalbed Methane Stream Depletion Study - Northern San Juan Basin, Colorado*, prepared by S.S. Papadopulos and Associates, Inc., dated Feb 2006 ("Report")

Dear Dick:

As you know, Maynes, Bradford, Shipps and Sheftel, LLP, represents the Southern Ute Indian Tribe ("Tribe"). Attached please find further comments of the Tribe on the Report. Thank you for your consideration of the Tribe's concerns. Because of the Tribe's major financial interest in coalbed methane ("CBM") development, the accuracy of any study dealing with stream depletions from CBM production is vital to the Tribe.

Sincerely,

MAYNES, BRADFORD, SHIPPS AND SHEFTEL, LLP

Janice C. Sheftel

Janice C. Sheftel

JCS:sps
cc: Dick Baughman
attachment
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re: Additional comments on *Coalbed Methane Stream Depletion Study –*
Northern San Juan Basin, Colorado, by S.S. Papadopulos and Associates,
Inc. ("SSP") Feb. 2006

Conceptual model

The hydrologic modeling portion of the Ignacio Blanco Field 3M study, performed in
2000 by Applied Hydrology Associates, Inc., shows that Fruitland Formation
permeabilities are variable, and that there are some areas that are partially or largely
compartmentalized, primarily evidenced by blocks of higher-TDS groundwater. In
contrast, the SSP Stream Depletion Study (Report) recognizes that "plumes" of low-TDS
water occur in the basin, but ignores the large areas of non-plume high-TDS water. The
Report also references studies by Riese and the Colorado Geological Survey (CGS), that
state that there are complex chemical and isotopic differences in the groundwaters
flowing through the coalbeds of the Fruitland Formation, and that these differences
indicate localized compartmentalization. The Glover method, required by the Division of
Water Resources ("DWR") for the Report, however, allows only one permeability value,
and thus is incapable of factoring in the effects of compartmentalization. The Glover
method, used to model hydrologic flow in the multi-permeable coalbeds of the Fruitland
Formation, is, therefore, inadequate.

The Report made two major assumptions: (1) uniform permeability, in order to provide
input values to the Glover equation, and (2) that any discontinuities do not have
"regional": effects.   Most importantly, the Report does not allow for reduction in water
permeability due to the relative permeability effects of desorption. In fact, the Report
excluded dual-phase flow dynamics, as being outside the scope of the Report. As soon as
CBM production starts, however, dual-phase flow dynamics quickly apply and these
dynamics always operate to reduce effective water permeability. In addition, coal
permeability reduces as the coal is depressurized. Ignoring this reduction in permeability
results in an over-estimation of stream depletion

All these factors, particularly relative permeability effects, result in an over-estimation of
stream depletion. The Report states that the Glover model is not applicable to the high
producing fairway due to the presence of gas, but, in fact, the same argument applies to
the entire area under CBM production.

Application of Glover method

The Glover method assumes an idealized and simplified stream-aquifer interaction, in
which the stream completely penetrates the aquifer and has perfect hydraulic connection
with the aquifer. In reality, the streams and alluvial bodies crossing the Fruitland outcrop
are shallow, partially penetrating, and may have reduced stream bed permeability.

All these factors lead the stream depletion to be overestimated by the Glover Method.

Additionally, the Glover method applies a uniform value of aquifer permeability, which is unrealistic.

Transmissivity and storage estimates

It is not clear why the Report's transmissivity estimates use image wells at outcrop boundaries, as this methodology ensures zero drawdown at the outcrop and may be unrealistic.

The Report does explain that the image well methodology is expected to reflect the effect of the higher storage values near the outcrop. Those higher storage values, however, were not used in The Report's Glover equation. As a result, the Glover method, using the wrong, lower storage values, greatly overestimates stream depletion, especially near the outcrop, which is the most important area from the point of view of stream depletion. The Report uses the Glover method with the wrong, lower storage values, but elsewhere points out that "…water level declines in the outcrop area of the aquifer will be very small, essentially, dampened due to the contrast in storage." (p.31).

The transmissivity estimates also assume a constant storage value, whereas, in reality, the area near the outcrop has a very large unconfined (porosity) storage value while the deeper parts of the basin have a much lower, confined (compressible) storage value.

The fact that there are large differences between the transmissivity determined for non-Ute monitoring wells and for Ute production wells indicates that (1) permeability is in fact very variable, and (2) relative permeability effects operate and are very significant in areas affected by production. Again, these estimates assume fully water-saturated conditions and do not take account of relative permeability effects, a significant drawback.

A further minor criticism of the Report is that SSP converted bottom hole pressure to water heads using a density of 2.307 g/mL which applies to fresh water, whereas some areas of groundwater are quite saline and, hence, denser.

Applicability of Glover method

Despite the shortcomings of the conceptual model, the transmissivity and storage estimates, and the use of the Glover method, described above, the Report suggests that "… the error associated with divergence from the ideal case can be minimized". The Report admits numerous sources of error,but does not provide convincing supporting evidence that error minimization has been achieved. Notably, the aquifer is not homogeneous or isotropic, and approximating to "average" values does not resolve that issue.

The input parameters of permeability and storage have basic flaws in the method of their determination and in the use of approximated values. As a result, these parameters are

likely to lead to significant over-estimates of actual outcrop influence and stream depletion.

The fact that the Glover method estimates stream depletion, under some scenarios, of over 500 ac-ft/year, whereas the estimated recharge to the Fruitland Formation over the entire San Juan Basin is only ~200 ac-ft/year, suggests that the Report pushes the envelope beyond the applicability of the Glover method. Several authors have addressed the shortcomings of the Glover method (e.g., Zlotnik et al, 1999, *Evaluation of stream depletion considering finite stream width, shallow penetration, and properties of streambed sediments*, in *Water 99 Joint Congress*, Brisbane Australia, July 6-8, 1999).

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HYDROSPHERE

Resource Consultants

May 3, 2006

Mr. Dick Wolfe, P.E.
Assistant State Engineer, Division of Water Resources
Department of Natural Resources
1313 Sherman Street, Room 818
Denver, Colorado 80203

Re: SSPA Report on Stream Depletion due to Coalbed Methane Development in the San
    Juan Basin, Colorado

Dear Mr. Wolfe:

With this letter, I summarize my findings and opinions related to the report entitled
Coalbed Methane Stream Depletion Assessment – Northern San Juan Basin, Colorado
prepared by S.S. Papadopulos & Associates and released by the State of Colorado on
April 4, 2006; below I refer to this as "the SSPA report." In general, I found the report to
yield results that understate actual expected stream, spring, and groundwater depletion.
To fully evaluate the amount of error in their depletion estimate would take a significant
amount of further data collection and analysis. The depletion underestimation error
relates to problems in their conceptualization and application of the Glover method.
Furthermore, the study completely fails to address the key issue of how seep and spring
flows, and drawdowns to shallow groundwater, in the outcrop area will be impacted by
water production of CBM wells. Given that there are numerous water users who rely on
supplies associated with springs, seeps, and shallow groundwater in the outcrop area, this
omission seriously limits the scope of the findings on how CBM production may impact
senior water rights in the northern San Juan Basin. After summarizing my findings and
opinions related to Chapters 1 through 5, I describe in detail my concerns related to their
depletion analysis.

Chapters 1 through 5

Chapter 1 of the SSPA report lists the project objectives to include an evaluation of the
suitability of the Glover method to estimate stream depletion due to northern San Juan
Basin CBM development. This chapter also lists sources of various data considered in
the report, including well production, stream and spring flows, water quality, and future
CBM production estimates. We have acquired and/or accessed all easily available

sources of hydrologic and hydrogeologic data (e.g., gas and water production histories), and these data agree with data as presented in the SSPA report (e.g., Figure 1.2). Chapters 2 and 3 provide broad descriptions of the geographic and geologic settings of the study area, and I found no glaring omissions or misstatements based on my previous independent reviews of data and information on the study area. Similarly, Chapter 4 on CBM production history and expected future trends seems appropriately targeted and accurate. Of particular interest in Chapter 4 is the fact that the "Fairway" area exhibits significantly higher gas-water production ratios compared to the other parts of the study area (inferred from Figures 4.3 and 4.4).   This fact coupled with lower derived permeabilities for Ute / Fairway area wells (presented subsequently in Section 5.3.2.2) suggests that the Glover-type hydrologic analysis may be inappropriate for estimating water depletions due to pumping wells in the Ute/Fairway area; this conclusion was also suggested by SSPA.

Chapter 5 describes hydrogeologic conditions in the study area as inferred from available data. Included in their analysis, SSPA employ water production and pressure data in conjunction with a Theis-type analysis to estimate permeability to be used subsequently in their Glover analysis. I concur with SSPA that using a simplified model built on the same assumptions as the Glover approach provides the most appropriate permeabilities to use in the Glover depletion analysis. Also notable in Chapter 5 is SSPA's finding, based on a review of a diverse set of hydrogeologic data and information, that a through-flowing aquifer conceptual model better matches observed conditions than a compartmentalized aquifer model promoted by some (Section 5.2.3). I also concur with this finding.

Chapter 6. CBM Produced Water Stream Depletion Analysis

In this Chapter, SSPA describes previous stream depletion studies for the area undertaken using a MODFLOW model, and they describe their approach for application of the Glover method. In describing their approach for applying the Glover method, they note that the streams actually cross the Fruitland – Pictured Cliffs outcrop in limited, discrete locations. They further describe that the streams "more resemble a series of small ponds in their intersection with the aquifer than they do linear streams" (p. 43 of SSPA report). I agree with this perspective. Then, however, they go on to note that between the streams along the outcrop zone are located tributaries, seeps, and springs. Based on this situation, they go on to argue that "when compared to the basin, the outcrop itself is stream-like."

While I agree that from the perspective of wells deep in the basin, the outcrop area is stream-like, I would argue that from the perspective of localized conditions along the outcrop, be it the major rivers, minor tributaries, or higher altitude springs and seeps, the hydrologic response of these features exhibit varying degrees of consistency with the Glover model. One of the key assumptions underlying the Glover method is that the stream can be represented as a constant head boundary that provides an essentially unlimited supply of surface water leakage into the aquifer to negate water level declines

that would occur in the absence of the stream. This assumption likely holds true for the major rivers, it is less true for tributary streams, and is likely patently untrue for seeps and springs. In fact, for these types of hydrologic features, the outcrop actually begins to exhibit conditions better represented by a no-flow boundary than by a constant head boundary.

The impact of a no-flow boundary would be a compounding of effects (i.e., depletions) on those features that act as constant head boundaries. In other words, depletions to the major streams and tributaries are likely larger than predicted by the Glover model. While one may contend that these compounding effects are actually lumped into the overall depletions computed using the Glover approach as implemented by SSPA, I would maintain that this is not necessarily true. In the higher outcrop areas, unconfined drainage likely does not approach the volumes of water needed to attenuate drawdowns to "appear" as constant heads in nearby portions of the aquifer. Rather, at this time based on my limited review without the benefit of having the basic data, it appears that the surface water depletion values computed by SSPA using their Glover model represent a minimum estimate with an unknown uncertainty.

Major Omission of Study: Impacts on Springs, Seeps, and Shallow Groundwater Levels in Outcrop Area

Beyond the concerns raised above related to estimated depletions to surface water flows, the actual hydrologic response likely involves a significant lowering of the unconfined water table in the higher elevation areas, causing seeps and springs to dry up, as well as shallow wells.   Consistent with the conceptual model of the Fruitland-Pictured Cliffs aquifer described by SSPA, one can envision the aquifer as a relatively flat confined system which is "upturned at the lip" (the outcrop area). In the outcrop area, conditions are unconfined (p. 34) and recharge to the aquifer occurs (p. 32). While SSPA acknowledges that in some cases springs in the outcrop may actually be discharging from the Fruitland-Pictured Cliffs (p. 33), based on my limited review it seems that an additional subset of the springs and first-order tributary flows in the outcrop area actually represent "rejected recharge" due to the unconfined water table intersecting the land surface (i.e., the aquifer is full and thus can accept no more recharge at that location).

Under these through-flowing aquifer conditions, one should reasonably expect that water extraction associated with CBM development will cause regional declines in water level that will propagate all the way to the outcrop. Such declines will directly impact spring and seep flows, as well as water level in shallow wells that penetrate the Fruitland – Pictured Cliffs aquifer. Water users who rely on and put to beneficial use these types of water supplies will be severely impacted by the CBM water production, and the Glover

analysis used to estimate depletions provide no way to evaluate this type of injury to senior water rights.[1]

Conclusions
This letter report summarizes my findings and opinions related to the SSPA report on expected water depletions due to CBM water production in the northern San Juan Basin of Colorado. While there are numerous aspects of the report that I agree with, with regard to expected water depletions, I found the report to yield results that understate actual expected stream, spring, and groundwater depletion. The depletion underestimation error relates to problems in their conceptualization and application of the Glover method, and I describe my concerns in detail above. To fully evaluate the amount of error in their depletion estimate would take a significant amount of further data collection and analysis. Finally, the report fails to explicitly address the expected water level declines to the unconfined portions to the Fruitland – Pictured Cliffs aquifer in the outcrop area, and how these water level declines will impact water users who rely on springs, seeps, and shallow groundwater in this area.

If you have any questions, please call me at 505-835-2569.

Sincerely,
Hydrosphere Resource Consultants, Inc.

by:_____
      James T. McCord, Ph.D., P.E.

Cc: Debbie Hathaway, SSPA

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[1] It is interesting to note that the SSPA report (as well as the AHA, 2000 and Cox et al., 2001 MODFLOW modeling reports) do not provide modeling results on expected water level declines in the outcrop area.

Appendix B

Estimation of Transmissivity and Storage Coefficient for the Fruitland Formation using Coalbed-Methane Observation and Pumping Data

APPENDIX B
Estimation of Transmissivity and Storage Coefficient for the Fruitland Formation using Coalbed-Methane Observation and Pumping Data

Estimation of transmissivity and storage coefficient for the Fruitland Formation involved five primary areas of analysis. First, observation data was obtained and formatted for use in model calibration. Second, water production data was obtained and formatted for use as model input. Third, a Theis analysis code was obtained and modified to calculate drawdown from historic pumping data. Fourth, PEST parameter estimation software was set up to optimize the fit between the Theis code calculated drawdown and the formatted observation data. Fifth, the model was calibrated to the observation data using PEST, resulting in calibration parameters for transmissivity and storage coefficient. These five areas of work are described below.

Observations

Observation data were compiled from a variety sources:

- *Observation Well Pressure Data*: This dataset was obtained by Debbie Baldwin of the OGCC. This dataset contains high frequency pressure readings obtained from dataloggers. Data involved are from 7 monitoring wells and 8 observation wells.
- *Questa Pressure Data*: This dataset was obtained off of the OGCC on-line library from Questa's report entitled: "The 3M Final Report". It contains pressure data from a number of wells. For this study, only high frequency data from 4 wells on the Ute reservation were used.

Pressure measurement location varied, with some wells measured at both the top and bottom of the borehole. Where well pressure data was measured at both the top and bottom of the well bore and depth of the top and bottom pressure transducers was available, well water levels were calculated. However, a significant number of the observation wells had considerable gas pressure in the borehole and, as a result, calculating the water level provided only a partial indication of the pressure in the formation. Therefore, for calibration purposes, only bottom pressure readings were used. Bottom pressure readings were converted to an equivalent water head by multiplying the pressure in psi by 2.307 to get feet of water head.

Both the lack of a consistent and reliable datum for the observation data set and the lack of depth to pressure transducer data for many of the wells precluded the possibility of working in water-head elevations. Instead, observations were used strictly in terms of cumulative change in water head from the first observation for each well.

Observation data were inspected and available associated metadata examined to identify data that should be eliminated. Data were then averaged on a monthly basis. Data were then formatted for use as model input files as follows:

- Data were consolidated into a single spreadsheet ("Hi Freq Pressure Input File v11112005.xls" or a later version)
- Data were copied into a formatting/processing spreadsheet ("timeseries.xls") and processed by performing the following steps
  - Data is copied onto "h" sheet and dh (change in head) calculated
  - Data in columns A – G is copied to "delh" sheet as values (no formulas)
  - On the "delh" sheet, cumulative dh values are copied to column C, overwriting the placeholder h values
  - From the delh sheet, data in columns A – E is copied to OBS.DAT. The cumulative observed change in water level data is placed in a formatted file, OBS.DAT. The file contains five columns
    - X coordinate in state plane coordinates

- Y coordinate in state plane coordinates
- Number of days since 1/1/1900 to the day of observation
- Cumulative head change (first value for each well is always zero)
- Well ID, which is not used by the code, but helps in checking the input file
  - o Data on the delh sheet is filtered on "Prefix"(column R) to exclude "-". Data in columns M – P is copied to the .PST file (the PEST control file) into the observation section. Data in column W is copied to .INS file.
  - o NOTE: In addition to the copy/paste explicitly outlined above, changes in the number of observations may require the modification of other information in OBS.DAT (the header), .PST (several of the control parameters), and the .INS file (the header).

Pumping Data

Water production history for 1686 production wells for the period January 1985 through August 2005 were obtained from the OGCC electronic database and the 3M modeling dataset. The OGCC electronic database covers the period January 1999 to August 2005; the 3M modeling dataset covers the period January 1985 through December 1998. In general, the two datasets meshed reasonably well. A change in the API identification of wells between datasets required some averaging of earlier data. However, the amount of production represented by these wells was not significant compared to overall water production rates and did not substantially affect parameter selection efforts.

Data were imported into an Access database and water production data converted from barrels per month (OGCC) and average barrels per day (Questa) to cubic feet per month (*TBL PW Data for Theis: Questa & COGCC – Original* in the Access database *Fruitland_SSPA.mdb*). Wells were assigned unique Well ID numbers consisting of concatenated State Code (05), County Code (007 or 067), Sequence No (XXXXX), and Sidetrack No (XX) (*TBL PW Data for Theis: Questa & COGCC – Formatted*). Easting and Northing location for each well, in State Plane Colorado South NAD27 US feet, was obtained.

Once the historic data was compiled, it was exported to a text file and formatted for the Theis analysis using the Fortran code *FormatTheisPumping.exe* (located in the *FormatFruitlandPumping* folder). For the Theis analysis, each change in pumping rate at a well, either positive or negative, is incorporated as a new well, with a start date equal to the date of change in pumping. Accordingly, for each well at each month of the historic record, the difference between current and previous month pumping was computed. If the result was non-zero, a new well was written to the formatted output file. Each new line was formatted as: Easting location, Northing location, change in pumping, start date (equal to the date of change in pumping, in days since 1/1/1900), Well ID. Pumping rate was converted to cubic feet per day, in keeping with the units used in the Theis code.

Boundaries

For the Theis analysis, model runs were made both with and without image wells. Image wells are required in situations where calculated draw-down impinges on boundary conditions; no image wells are required for simulation of an effectively infinite plane. Since, a priori, the appropriate application for the San Juan Basin was unknown, and since developing and testing first the historical pumping data alone, and then the pumping data with the addition of image wells, both scenarios were run.

For the image well analysis, each production well was matched with an image well located an equal distance from the Fruitland outcrop to the outside of the outcrop, injecting water at monthly rates equal to the production well pumping. Image well locations were generated by fitting a line through the center of the Fruitland outcrop, calculating the minimum vector distance between each production well and the outcrop center-line, and projecting along the same vector an equal distance to the paired image well. The formatting code was modified to print two wells to the file for each change in pumping. Each image well duplicated a pumping well entry but with a negative change in pumping, the image well's Easting and Northing locations, and an "I" prefacing the Well ID.

Theis Code

A FORTRAN code was used to calculate drawdown based on the Theis equation for drawdown in a single well, and the principal of superposition. The code, THEISMODEL.FOR, reads the pumping data file (THEISMODEL.DAT) and the observation file (OBS.DAT).

The THEIS code was tested on data provided by its author, Steve Larson. The code was then modified so that it would work with head differences, instead of elevation heads. The same data set was used to test the modifications. THEIS starts by reading in all of the pumping data and storing it in arrays. The code next starts a loop to read information on each of the observation wells from OBS.DAT. Each loop takes the location and time of an observation and then starts looping through the pumping data accumulating the drawdown for each pumping stress that occurs prior to the observation date. If it is the first observation well, the cumulated drawdown is used as an offset so that the first value is set to zero and subsequent terms are adjusted by the initial offset. The observation loop continues until all observations from all wells are written to the output file, THEIS.OUT

PEST Setup

PEST runs were set up to estimate parameter values that provided the best fit between simulated and observed values. The files associated with the PEST run consist of:

- THEISMODEL.PST: the PEST control file
  - o control values for PEST execution
  - o listing of parameters, in this case 8 are listed but only two (transmissivity and storage coefficient) are actually used
  - o list of the observation groups (data from each observation well is an observation group for this case)
  - o list of the observation name, observation values, weight (uniform in this case) and observation group
  - o file names associated with the PEST run
- THEIS.EXE: the Theis model executable
- OBS.DAT: the observation input file for the model run.
- THEIS.INS: PEST instruction file which tells PEST how to read the model output file (THEIS.OUT) and extract the correct information for the simulated values.
- THEIS.OUT: Model output file
- THEISMODEL.TPL: PEST template file. This file is almost a copy of the pumping file, THEISMODEL.DAT, but has some special control characters so that PEST can replace parameter values as it progresses through a parameter estimation run.
- THEISMODEL.DAT: This is the formatted pumping input file for the model. This file is the same as THEISINPUT.DAT, only the name was changed to correspond to the hardwired name in the THEIS code.

PEST uses the Gauss-Marquardt-Levenburg algorithm to find a minimum of the objective function for a given model by adjusting the parameters. The objective function is proportional to the weighted residuals between measured and modeled values. PEST begins with an initial set of parameter values, provided by the user, and runs the model to evaluate the objective function. This can be considered the initial base run. Next PEST slightly modifies each of the parameters in the model and for each modification performs a model run having only a single parameter changed from the base run. PEST analyzes the changes due to the individual parameter adjustments and determines a change in parameter values that will improve the fit between measured and modeled values. This new set of parameters is used as the new base run and the process repeated. Each repetition is intended to provide an improved fit between measured and modeled parameters. If the fit does not improve PEST continues for a user defined number of iterations attempting other parameter combinations and, if unsuccessful, calculates final statistics and reports the best-fit parameter values, even if those parameter were not from the final iteration.

Calibration Runs
Model runs revealed a significant difference in the response of one set of four wells (API #'s 07958, 07959, 07054, 07120), referred to as the Ute wells, versus all others, collectively referred to as the non-Ute wells. Attempts to determine a single set of parameter values forced a considerable compromise in parameter values and produced a poor fit between the observed and simulated values. As a result the observation data was split into two sets and parameters were estimated for two sets of data: the non-Ute wells and the Ute wells.

PEST runs using observation data from the non Ute wells produced estimates of transmissivity and storage coefficient of 1.2 ft^2/day and 3.1E-04, respectively. Measured and modeled values are shown in Figure B.1. (Note, wells were divided into the three groups shown based on well number; division is for graphical presentation only.)

PEST runs using observation data from the Ute wells produced estimates of transmissivity and storage coefficient of 0.076 ft^2/day and 9.0E-06, respectively. Measured and modeled values are shown in Figure B.2. Based on the pumping stress supplied to the Theis model, the Ute wells required these small transmissivity and storage coefficient values in order for the modeled drawdowns to be similar to the measured. Attempts to use parameter values similar to the non-Ute wells produce modeled values that were significantly less than measured. While a number of explanations are possible, it seems likely that the water-production data in the area of the Ute wells does not provide a good indication of the change in formation pressure: several production wells in the vicinity of the Ute wells produce very little water (e.g., API # 07751, 07584). The Theis model uses water pumped to indicate the change in piezometric head in the formation. If pressure changes are primarily due to pumping of gas, water pumping data alone is not sufficient input to the Theis model.

Model runs made with and without image wells produced virtually identical results, indicating that results are not sensitive to the presence of the boundary for the time-period modeled.

Figure B.1.
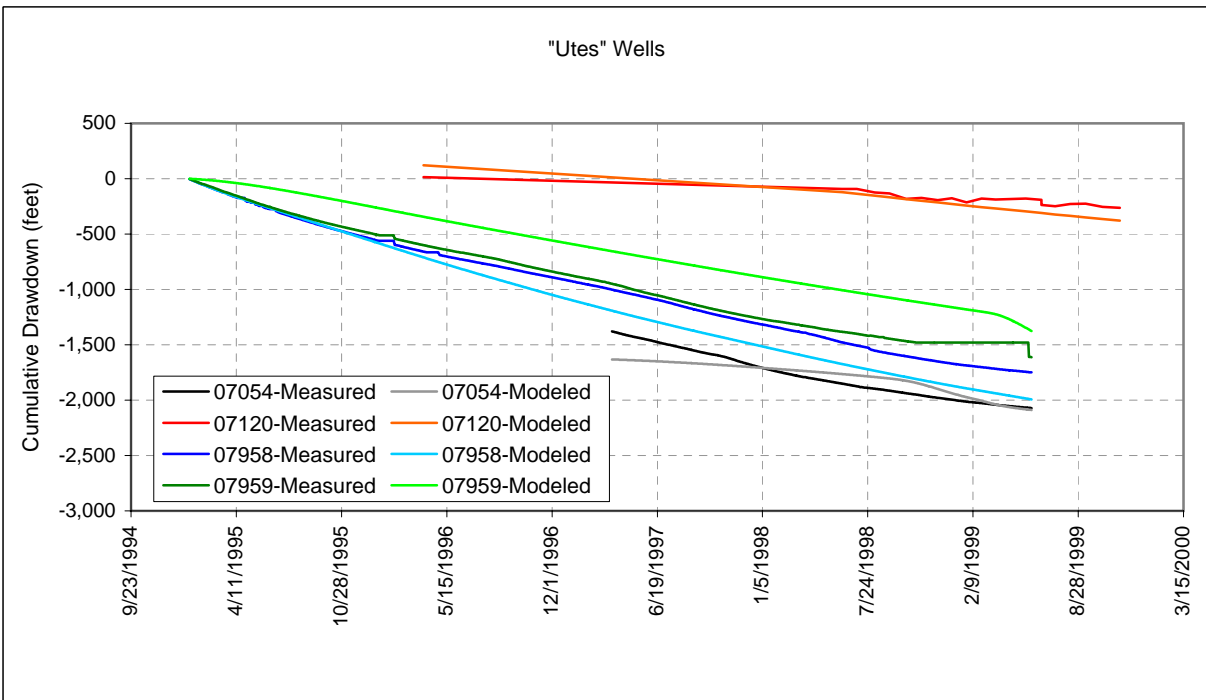**Modeled vs. Observed drawdown, "No-Ute" Wells Simulation**
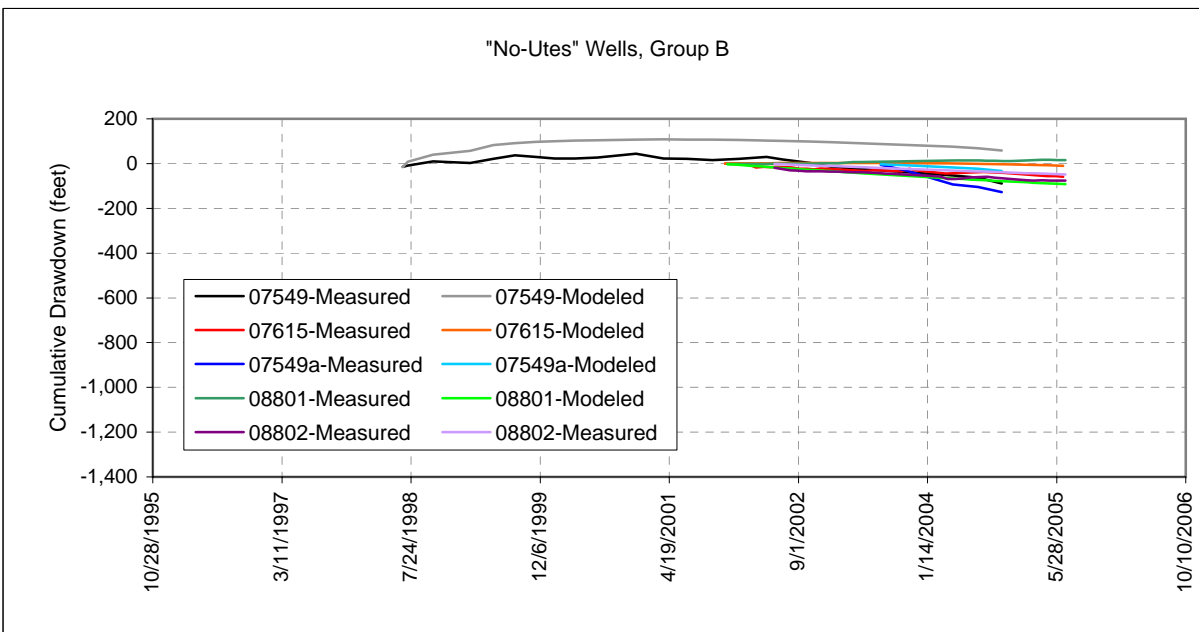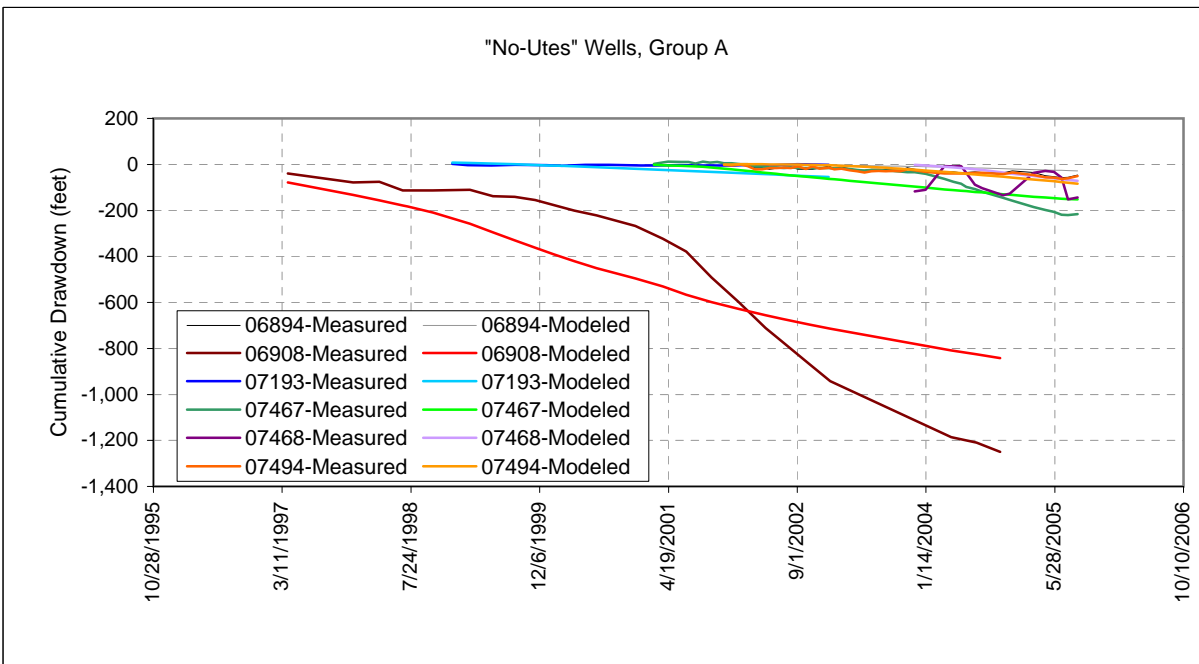
Figure B.1.
Modeled vs. Observed drawdown, "No-Ute" Wells Simulation (continued)

"No-Utes" Wells, Group C
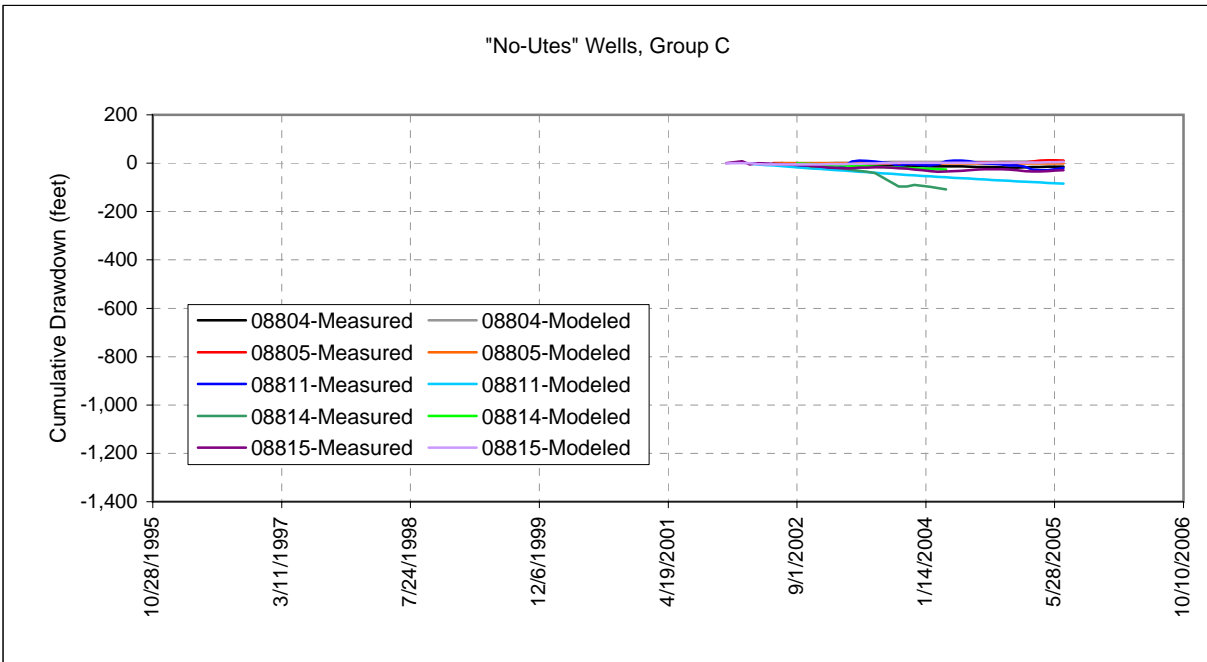
Figure B.2.
Modeled vs. Observed Drawdown, "Ute" Well Simulation

Appendix C

Estimating Surface Water Depletions Resulting from Fruitland Formation Pumping using the Glover Balmer Analytic Solution

APPENDIX C
Estimating Surface Water Depletions Resulting from Fruitland Formation Pumping using the Glover Balmer Analytic Solution

Using transmissivity and storage coefficients estimated for the Fruitland Formation with an analytic Theis solution, the Glover Balmer Analytic Solution was used to estimate current and potential future depletions to surface water flows. This analysis can be broken into three components: preparation of well pumping data required for the Glover Balmer analysis; application of a Glover Balmer code to solve for depletions; review and assessment of depletions results.

Pumping Data
To apply the Glover Balmer analysis, well pumping rate, timing of pumping onset, change, and termination, and distance from well to depletion site (e.g. the Fruitland Formation outcrop) are required. The water production history for the existing 1,686 San Juan Basin production wells compiled for the Theis analysis was used in the Glover Balmer depletions analysis. Future pumping was estimated as discussed below. Distance to outcrop was generated by fitting a center-line through the Fruitland outcrop and calculating the minimum distance between each production well and the outcrop center-line. This distance may vary slightly from the distances calculated for the Theis image well placement work since the actual Formation center-line was used rather than an arcuate approximation of the center-line.

Historic water production data for the San Juan Basin production wells is exported to a text file and formatted for the Glover Balmer code using the Fortran code *FormatPumpingDatafor FutureDepletionsAnalysis.for*. As for the Theis analysis, each change in pumping rate at a well, either positive or negative, is incorporated as a new well, with a start date equal to the date of change in pumping. Accordingly, for each well at each month of the historic record, the difference between current and previous month pumping is computed. If the result is non-zero, a new well is written to the formatted output file. Each new line is formatted as: change in pumping, start date (equal to the date of change in pumping, in days since 1/1/1900), distance to outcrop, and well ID. The pumping rate was converted to cubic feet per day, in keeping with the units used in the Glover Balmer code.

Historic pumping data is available through August 2005. Beginning September 2005, historic wells are evaluated for pumping lifetime. Wells are turned off once they have pumped for 10 years. Wells that have pumped 10 years or more by September 2005 are turned off in September 2005. Historic wells with additional lifespan are adjusted on September 2005 to pump at a constant rate equal to the average daily pumping recorded for January 2005 through August 2005. Pumping is then maintained at this rate until the well lifespan reached 10 years, at which point the well is turned off[1].

For future depletions analysis, input data characterizing estimated future pumping was required. Future pumping is estimated in three stages: first, projected new well development is determined; second, new wells are positioned within the basin; and third, new wells are assigned an average pumping rate, start date, and end date.

Projected new well development is based on information provided in current and historic well down-spacing orders for the basin (available for review on the OGCC website, http://oil-gas.state.co.us/), on the scenarios presented in the Draft EIS (BLM, 2004), and on the basis of information provided by OGCC personnel (D. Baldwin, personal communication, November 29, 2005). The spacing patterns being established in current and historic down-spacing orders were used as the basis for spacing on the Ute lands. On Ute lands, sections with 320 acre spacing were left unchanged; sections with 160 acre spacing were projected to move to 80 acre spacing. For the area north of the Ute lands, alternative 2 of the draft EIS was applied, essentially resulting in 160 acre spacing.

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[1] For application in the Glover Balmer code, "turning off" a well consists of adding a new well to the file which injects water at a rate equal to the pumping rate which has turned off, thus offsetting the continued pumping of the well as implemented in the code.

Projected future spacing is applied at the section scale. Total number of wells predicted within each section is calculated based on the above criteria. This is then compared to the existing number of wells within the section to determine the total number of new wells predicted within each section. For each section with a non-zero number of predicted new wells, one new well is assigned to the section. This new well is located at the center of the section.

Pumping rates for new wells are based on average historic pumping rates for all historic wells over the entire period of historic data. The average daily pumping rate taken from the historic data is approximately 360 cubic feet per day. Average pumping for each section is calculated by multiplying 360 cubic feet per day by the number of predicted new wells within the section.

Future wells are turned on at a rate of approximately 50 single-well equivalents each 6 months, beginning in January 2006. Wells are turned on by section, with new wells at 320 acre spacing turned on last. Wells are run for ten years, and then turned off.

Once the future well data is compiled, it is formatted for the Glover Balmer code using the Fortran code *FormatHypotheticalWells.for*. As for the historic data, output is formatted as: change in pumping, start date (equal to the date of change in pumping, in days since 1/1/1900), distance to outcrop, and well ID. Pumping rate is converted to cubic feet per day, in keeping with the units used in the Glover Balmer code. Well ID is set equal to the Township, Range, Section the well is located in. The output file created by *FormatHypotheticalWells.for* only contains data for the projected new wells and is therefore designed to be appended to the Glover Balmer input file (e.g. *pumping.dat*) rather than function as a stand-alone file.

Two future pumping scenarios are examined, one allowing pumping within a 1.5 mile buffer of the Fruitland outcrop, and one prohibiting pumping within a 1.5 mile buffer of the outcrop. Data for the buffered future scenario omits future wells in sections where the center of the section was within the 1.5 mile buffer zone. Wells falling within the buffer zone are omitted from the input data provided to *FormatHypotheticalWells.for* without further change to the file. This implies that in the buffered scenario, in many 6 month periods fewer than 50 wells are brought on-line. However, it preserves the full timeline for phase-in and retirement of wells established in the un-buffered scenario.

Glover Balmer Code
A FORTRAN code is used to calculate depletions based on the Glover Balmer equation for depletions on a boundary stream. The code, GloBalQs.FOR, reads a pumping data file (e.g. *pumping.dat*) and stores pumping data in arrays. The code loops through all of the pumping data, summing depletions for each well. Depletions are calculated using the pumping start date and pumping rate specified for each well in the input file, and a date at which depletions are to be evaluated which is specified in line 3 of the input file. When depletions from all wells have been summed, output is written to the output file GlvBlmQs.sum.

Model Runs
The model is runs for four scenarios:

- To assess depletions to date (August 2005) using historical pumping data
- To assess future depletions as a function of time using historical pumping data, with existing wells turned off after 10 years of pumping
- To estimate future depletions as a function of time, using historical pumping and projected new wells; new wells are prohibited within 1.5 miles of the Fruitland outcrop
- To estimate future depletions as a function of time, using historical pumping and projected new wells; new wells are allowed within 1.5 miles of the Fruitland outcrop

Results from these depletion analyses are shown in figure C.1. The difference between the buffered and un-buffered future scenarios is quite dramatic. To evaluate the accuracy of this result, single-well analyses were run for wells at 1, 2, and 4 miles from the outcrop, and the percentage of pumping depleting the outcrop over time plotted. The results of this analysis are shown in Figure C.2.

Figure C.1.
Net Fruitland-Outcrop Depletion Rate
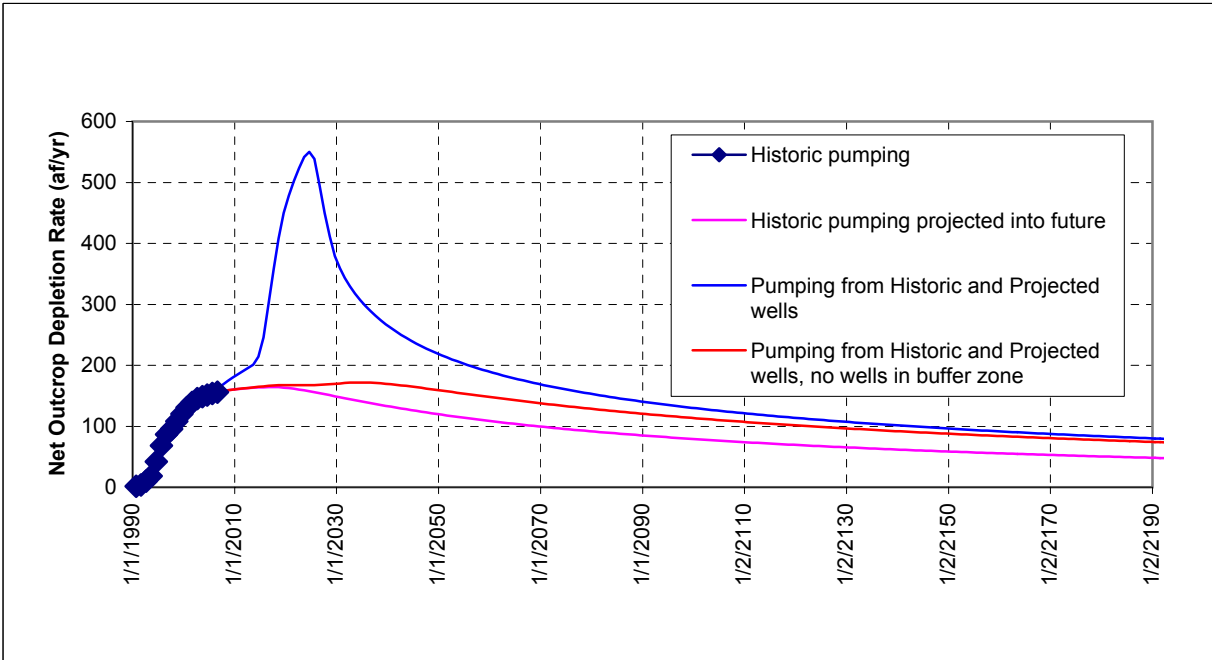
Figure C.2.
Net Fruitland-Outcrop Depletion Rate Single-will Depletion Tests
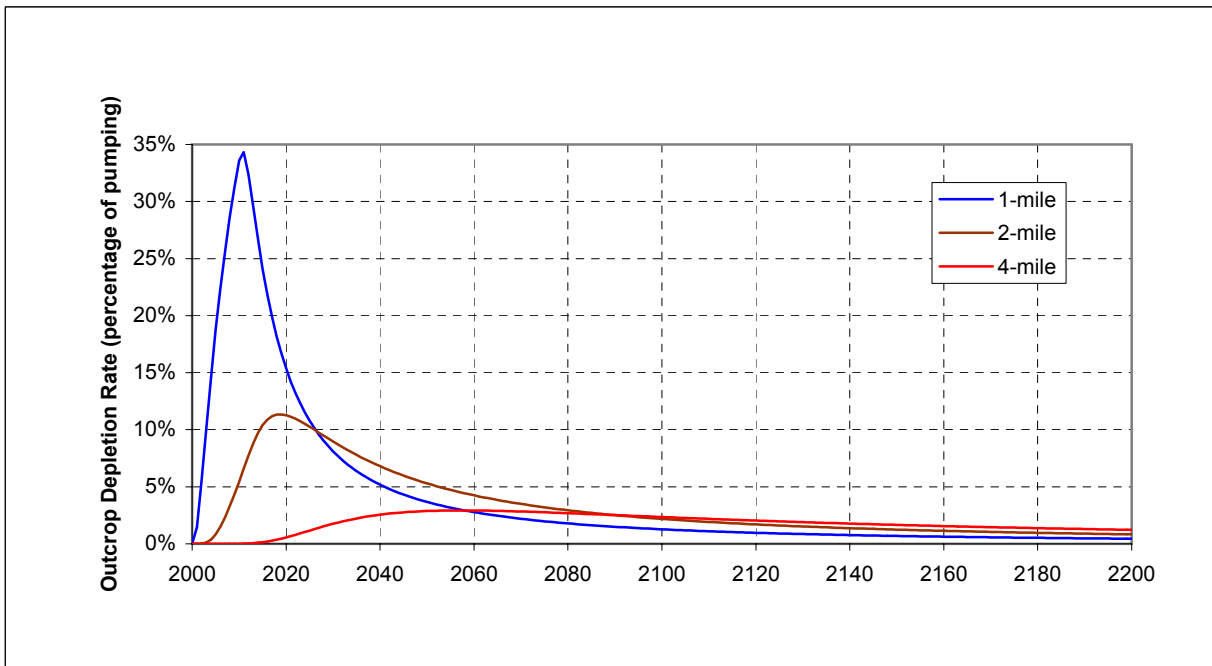
Note: well pumping started in 2000; wells pump for 10 years and are then stopped

Appendix D

Water Rights and Beneficial Use of Coal Bed Methane Produced Water in Colorado (Source: Colorado Division of Water Resources, October 2002)

Water Rights and Beneficial Use of Coal Bed Methane Produced Water in Colorado

By

Dick Wolfe, P.E.
&
Glenn Graham, P.G.

Denver, Colorado

October 2002

1.0 Objective

Water is a scarce and valuable resource in Colorado. Any activity that appears to waste it or that may waste it creates challenges as well as potential opportunities. The beneficial use of produced water from coal bed methane (CBM) wells is one such potential opportunity that also raises challenges. This paper explores the state laws and regulations in Colorado governing the use of produced water. This paper does not attempt to address county or local laws and regulations, which are beyond its scope.

2.0 Types of Ground Water

In Colorado, there are basically five types of ground water that are administered by the Colorado Division of Water Resources (CDWR) and the Colorado Ground Water Commission (CGWC). The CGWC has primary authority over the administration of designated ground water. The five types are as follows:

Tributary

Ground water that is hydrologically connected to a natural stream system either by surface or underground flows.

Nontributary

Ground water located outside the boundaries of any designated ground water basin. The withdrawal of this ground water by a well will not, within 100 years, deplete the flow of a natural stream at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal.

Not-nontributary

Ground water located within those portions of the Dawson, Denver, Arapahoe, and Laramie-Fox Hills aquifers that are outside of any designated ground water basin in existence on January 1, 1985, the withdrawal of which will, within 100 years, deplete the flow of a natural stream at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal.

Designated

Ground water that, in its natural course, is not available to or required for the fulfillment of decreed surface rights, or ground water in areas not adjacent to a continuously flowing natural stream, wherein ground water withdrawals have constituted the principal water usage for at least 15 years preceding the date of the first hearing on the proposed designation of the basin, and which is within the geographic boundaries of a designated ground water basin.

Geothermal

Ground water that contains geothermal energy.

3.0 Geologic Factors Affecting Water Production

CBM gas in Colorado is produced from coal seams that were created by the deposition of large amounts of organic material in fluvial and marginal marine environments adjacent to the western margin of the Western Interior Cretaceous Seaway during late Cretaceous and early Tertiary time.

The coals are interbedded with mudstones or claystones and sandstones, and are predominately lenticular in cross section and laterally discontinuous. These coal seams vary in thickness from a fraction of an inch to several feet. In a few limited areas, individual beds may be more than 10 feet thick. The individual beds may be spread vertically over several hundred feet of stratigraphic section. The coal bearing sequences are found cropping out on the surface or as deep as 5,000 feet below the surface. At this time, most CBM production in Colorado is from coal seams that are less than about 3,000 feet below the surface.

Some of the geologic formations containing existing or potential CBM resources in Colorado are the Raton and Vermejo formations in the Raton Basin; the Denver and Laramie formations in the Denver Basin; and formations within the Mesa Verde Group, found in several basins on the western slope of the state.

CBM gas is molecularly adsorbed on crystal surfaces of the coal, and is held there under the hydrostatic pressure of the water contained in the coal beds and the adjacent sandstones. In order for the CBM gas to be liberated or desorbed from the crystalline structure of the coal, the hydrostatic head, or the reservoir pressure in the coal seam, must first be reduced. This pressure reduction is accomplished by dewatering the coal seams. To further enhance the productive ability of the coals, hydraulic fracturing techniques are used to increase the permeability of the coal seams.

A typical CBM well is drilled and cased through the potential productive interval. Selected intervals containing the coal seams are perforated and hydraulically fractured, and a down-hole pump designed to remove large quantities of water is installed. When first placed on-line, a CBM well will produce significant amounts of water with little or no gas production. Ideally, within a month or two of being placed on-line gas production will start to increase and water production will start to decrease as the coal seams become dewatered. After a year or two of production, water production rates can fall to as little as a few barrels of water per day for individual wells, while daily gas production rates will increase from essentially nothing to several hundred thousand cubic feet or more per day.

Ideally, the water produced by the CBM extraction process is water that was contained in only the coal seams, and not water contained in other parts of the stratigraphic column. Because of the highly layered or interbedded and lenticular nature of the geologic formations that contain CBM resources, there are significant barriers to the vertical movement of water. Given the amount of water being produced during the early life of a CBM well, there has been some concern that there may be some impact to water bearing zones that might be of suitable quality to be a source of water for residential, stock watering or irrigation purposes. At this point in time in Colorado, no documented incidents of direct impact on existing water wells from nearby production of CBM gas have been reported to CDWR.

Another concern identified is the possible effect on stream systems that flow across the outcrop areas of coal-bearing formations. Again, the highly interbedded and lenticular nature of these geologic formations may limit or effectively disconnect the stream systems from the zones from which the water is being produced. This is an area where further study is certainly warranted.

Historically, CBM produced water in Colorado has typically not been of suitable quality for any beneficial use, and only recently has some of this produced water been of good enough quality for some limited beneficial uses. For the most part, beneficial use of produced water in the San Juan Basin has not been proposed, because the quality of produced water in that area is too poor for

most uses, but some concerns have been raised regarding potential effects on surface water flows. In the Raton Basin of southern Colorado, approximately 5 Mgal/day of ground water is produced from CBM wells. Of this amount, approximately 30% is discharged to natural streams, 30% is reinjected and 40% is discharged to evaporation pits. The 1.5 Mgal/day that is discharged to the natural streams is done under discharge permits issued by the Colorado Water Quality Control Division (CWQCD) of the Colorado Department of Public Health and Environment (CDPHE) via approximately 40 discharge points (equal to approximately 26 gpm on average per discharge point). Proponents of the use of this produced water should keep in mind that the volume of water being produced will typically decline quite rapidly during the first year or so of production, and may approach nothing after a few years. Further, the economic life of a CBM well may not exceed 10 years.

Other basins in the state are being evaluated for CBM potential, but no development has occurred to this point in time. Those basins are the southeast part of the Piceance Basin in Delta County, the southeast part of the Greater Green River Basin, and the Denver Basin.

In addition to the physical limitations described above, there presently are significant legal and institutional barriers to the beneficial use of CBM produced water.

4.0 Jurisdiction Over Produced Ground Water

4.1 Historical Perspective

The desire to use water from CBM wells has only recently surfaced because the quality of water from CBM wells has never been good enough for most uses. Multiple agencies regulate and monitor various aspects of produced ground water, yet no agency oversees and integrates all aspects. Each agency has its own jurisdiction as established by enabling laws. At least three different agencies (the Colorado Oil and Gas Conservation Commission (COGCC), CDWR, and CWQCD) have authority as it relates to the withdrawal, use, and/or disposal of water from a CBM well, and the relationships between the constitutional provisions, statutory language, and various rules are extremely complex.

CDWR is aware of overlapping jurisdictional issues between the COGCC and CWQCD. COGCC has authority over all oil and gas operations, including the generation, transportation, storage, treatment, or disposal of exploration and production wastes. Water removed from a CBM well is considered a waste product. The CDPHE rules provide that no person shall discharge CBM produced water into waters of the state without first having obtained a permit from CWQCD for such discharge.

4.2 Allowed Beneficial Uses and Restrictions of Ground Water

Whether a use is beneficial is a question of fact and depends on the circumstances of each case. However, the following uses have been recognized as beneficial uses by CDWR: agriculture, mining, domestic, manufacturing, stock watering, wildlife watering, irrigation, industrial, mechanical, commercial, municipal, recreation, minimum stream flows, fire protection, and dust suppression.

CDWR has jurisdiction over appropriations of water. An appropriation is defined as the application of a specified portion of the waters of the state to a beneficial use pursuant to the procedures prescribed by law. Waters of the state in this context means all surface and underground water tributary to natural streams, except designated ground water as designated by

the CGWC. The statutory and case law vests CDWR with jurisdiction over water withdrawn from a CBM well that is beneficially used.

If an operator or another person wants to beneficially use water from a CBM well, that operator or person must comply with the Water Right Determination and Administration Act and the Ground Water Management Act (Water Rights Acts). The person could apply for a water right in water court and/or file for a well permit. If the person applies for a well permit for water from a CBM well, that water is presumed tributary, but the person may submit evidence such as engineering documentation that the water is nontributary. Regardless of whether the water withdrawn from a CBM well is nontributary or tributary, there are certain statutory requirements that the water user must meet before obtaining a well permit and/or a water court decree. Any water discharged into waters of the state (as defined by the Water Quality Control Act) is subject to appropriation under the Water Rights Acts.

CBM wells are not "wells" as defined in the Water Rights Acts, and operators do not need to obtain a permit from CDWR to withdraw water from these wells as part of the CBM extraction process. However, if water from a CBM well is put to beneficial use other than those uses allowed under COGCC Rule 907 (see below), then CDWR has certain jurisdiction over the water and the well, and the well is subject to the *Rules and Regulations for Water Well Construction, Pump Installation, and Monitoring and Observation Hole/Well Construction (2CCR 402-2).*

4.2.1 COGCC Rule 907

The COGCC statute (COGCC Act) grants certain authority to COGCC to promote oil and gas conservation, and rescinds any authority of any other agency as it relates to the conservation of oil and gas. CBM produced water is considered a waste product by operators and must be properly disposed of to prevent adverse environmental impacts. Pursuant to COGCC rules, an operator may dispose of water from a CBM well in any of the following ways: 1) inject into a disposal well; 2) place it in a properly permitted lined or unlined pit for evaporation and or percolation; 3) dispose the water at a permitted commercial facility; 4) dispose of the water by road spreading on lease roads outside sensitive areas for produced waters; 5) discharge the water into waters of the state in accordance with the Water Quality Control Act and the rules and regulations promulgated thereunder; 6) reuse the water for enhanced recovery, recycling, and drilling; or 7) mitigation to provide an alternate domestic water supply to surface owners within the oil and gas field.

4.2.2 Ground Water Permitting by CDWR

Under Colorado law, CBM operators are not required to obtain a permit from the State Engineer when withdrawing nontributary water unless the produced water is put to a beneficial use. The State Engineer has authority to issue permits outside designated basins in accordance with section 37-90-137(7), CRS (2002), which is restated as follows:

In the case of dewatering of geologic formations by removing nontributary ground water to facilitate or permit mining of minerals: (a) No well permit shall be required unless the nontributary ground water being removed will be beneficially used; and, (b) In the issuance of any well permit pursuant to this subsection (7), the provisions of subsection (4) of this section shall not apply. The provisions of subsections (1), (2), and (3) of this section shall apply; except that, in considering whether the permit shall issue, the requirement that the state engineer find that there is unappropriated water available for withdrawal and the six-hundred-foot spacing requirement in subsection (2) of this section shall not apply. The state engineer shall allow the

rate of withdrawal stated by the applicant to be necessary to dewater the mine; except that, if the state engineer finds that the proposed dewatering will cause material injury to the vested water rights of others, the applicant may propose, and the permit shall contain, terms and conditions which will prevent such injury. The reduction of hydrostatic pressure level or water level alone does not constitute material injury.

In the context of this section, the State Engineer considers CBM gas a mineral. As stated above, if ground water produced from a CBM well is determined to be nontributary, the amount of water claimed is not based on overlying land ownership. If nontributary ground water is produced to the surface and discharged, it may be subject to CWQCD regulation.

For water rights purposes, all ground water in Colorado is presumed to be tributary unless there has been a ruling by the water court or a permit issued by the State Engineer that ground water from a certain aquifer in a specific area is declared nontributary. Any beneficial use of tributary ground water is subject to section 37-90-137(1) and (2), CRS (2002). Any use of tributary ground water requires a well permit and a determination by the State Engineer as to whether or not the exercise of the requested permit will materially injure the vested water rights of others. Also, the requirement that the State Engineer find that there is unappropriated water available for withdrawal and the six-hundred-foot spacing requirement in subsection (2) of this section shall apply.

5.0 Conclusions

A rough assessment of the opportunities to use produced water from CBM wells is that they are limited at best. Much of the water is too poor in quality to be legally discharged. Because most basins are over-appropriated, senior water rights claims complicate the issue. Because water production rates from CBM wells decline as gas is produced, CBM wells are unreliable as long-term sources of water. In limited areas where produced water quality is sufficient and vested water rights owners would not be injured, there may be some opportunities for beneficially using water produced from CBM wells in the short term. Such opportunities are not without cost or legal and technical complication.

Due to the complex and overlapping regulatory authority of state agencies, many companies are collaboratively working with local residents, concerned citizens, and state agencies to mitigate and minimize impacts of CBM production. It has been only recently that the CDPHE, COGCC, and the CDWR have coordinated efforts to understand and minimize the conflicts in regulatory authority and decision-making. These efforts have resulted in many public awareness meetings with both the general public and legislative committees on oil and gas. New rules and regulations were adopted by the COGCC to clarify jurisdictional uses of CBM produced water. The state must continue to educate and communicate with citizens and industry representatives to understand the impacts of CBM development and the statutory and regulatory environment in which it occurs.