Coalbed Methane Stream Depletion Assessment Study –

Raton Basin, Colorado

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EXECUTIVE SUMMARY

The Raton Basin produces a significant amount of coalbed methane (CBM). Typically, in conjunction with the production of CBM is the production of water. In the Raton 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 that could impact water rights holders, the State of Colorado, and downstream water users not in Colorado. For these reasons it was considered important to evaluate the extent and impacts of CBM water production in the Raton Basin in the context of the regulatory framework associated with the production of CBM water.

To promote communication and facilitate this evaluation of conditions in the Raton Basin in Colorado, a public meeting was advertised and held in Trinidad on January 24, 2007. 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 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 supported this study, along with the contracting agency, the Colorado Geological Survey. 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 Raton 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 Raton 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.

Since the initial production of CBM in the basin in the mid 1980s, over 500 billion cubic feet (Bcf) of gas have been produced from approximately 2,000 wells in the Colorado portion of the basin. CBM in the Raton Basin is produced from the coals in the Vermejo and Raton Formations. Projections of annual production for 2006, based on the first six months of the year, indicate that gas production may reach 85 Bcf and water production may reach 16,000 acre-feet.

A stream depletion analysis was conducted for approximately 2,000 Vermejo and Raton Formation CBM wells to quantify current and expected future depletions of surface water due to CBM-related groundwater extraction. The analysis developed impacts separately for the

Purgatoire and the Cucharas rivers, as a function of well location and producing formations. Aquifer parameters for the Purgatoire River depletion analysis were developed from hydraulic test values and other hydrogeologic information found in the literature. No fluid pressure were available to this study from CBM producers in the Purgatoire River watershed or surrounding areas; therefore, independent estimation of hydraulic parameters through inverse methods was not possible in this part of the study area. Conversely, in the Cucharas River watershed and surrounding areas, very little hydrogeologic data are found in the literature; however, some fluid pressure data was made available to this study by a producer and this information was used to estimate hydraulic properties of the producing region. The stream depletion analysis indicates that the present magnitude of stream depletion from all wells producing in the Colorado portion of the Raton Basin is approximately 2,500 acre-feet per year.

The results of the stream depletion analysis were considered in conjunction with statutory criterion for delineation of a "non-tributary" 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. Applying this criterion, groundwater in all areas of current CBM production in the Colorado portion of the Raton Basin would be considered "tributary". Because of the uncertainty in hydraulic parameters associated with the stream depletion analysis, a sensitivity analysis was conducted with other parameter values. The sensitivity analysis suggests that the same conclusion would be reached under a wide range of alternate parameter assumptions. Nevertheless, if fluid pressure data and test data developed by all producers were to be made available, the range of uncertainty in calculated stream depletion impacts could be narrowed and more accurate stream depletion estimates could be developed.

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.

The water quality of produced water in the Raton Basin, with total dissolved solids concentrations typically less than 7,000 mg/L, is such that beneficial use, for example, for stock watering or irrigation, is not precluded. Because the waters of the Arkansas River are subject to control under the Arkansas River Compact, and waters in this basin are considered fully appropriated under most circumstances, stream depletion impacts require careful consideration.

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1.0 INTRODUCTION

1.1 Background

The Raton Basin extends from southern Colorado into northeastern New Mexico (Figure 1.1). Since the initial production of coal bed methane (CBM) in the basin in the mid 1980s, over 500 billion cubic feet (Bcf) of gas have been produced from approximately 2,000 wells in the Colorado portion of the basin. Estimated CBM reserves for the basin are nearly 1,600 Bcf of gas in place (USGS, 2005; Higley and others, 2007).

In conjunction with the production of CBM is the production of water. There are concerns with the amount, quality, uses, and effects of CBM produced water in the Raton Basin in Colorado and with how the production of water may be affecting methane gas seepage at the surface. This study focuses on one of these concerns: whether the removal of water from aquifers that may be tributary to the surface stream system in the Raton Basin could cause stream depletion and injure senior water rights holders.

The production of CBM in Colorado is regulated by the Colorado Oil and Gas Conservation Commission (COGCC). However Colorado 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 both ensuring efficient production of CBM and in protecting the state's water resources, these two agencies, and the Colorado Geologic Survey [CGS], have commissioned this study to evaluate the magnitude of stream depletions from CBM production.

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 Raton Basin as it relates to the production of CBM and CBM produced water;
- To implement and evaluate the suitability of the Glover analysis (Glover and Balmer, 1954) as a stream depletion analytical tool for administering CBM water production in the Raton 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 coal bearing formations) that may be occurring as a result of the removal of water by CBM wells.

1.3 Scope of Work

CBM in the Raton Basin is produced from the coals in the Vermejo and Raton Formations. This study examined existing information relating to the geographic setting, geology, hydrogeology, CBM gas and water production, and water chemistry of these coal-bearing 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 Trinidad on January 24, 2007, 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 from other interested parties 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 was conducted to quantify current and expected future depletions of surface water due to CBM groundwater extraction. 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. The study further examined regulatory and other issues regarding use of CBM produced water.

The goals of this study are to provide background regarding CBM production and to evaluate stream depletion associated with CBM production. 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 were not included in this study is not a reflection of their importance; rather, it is a reflection of the focus of this study on evaluating stream depletion.

1.4 Report Organization

Chapter 2 summarizes available data and resources. Chapter 3 describes the physical and geologic setting of the Raton Basin. Chapter 4 describes the nature of CBM gas and water production. Chapter 5 describes the hydrogeologic setting. Chapter 6 provides 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 Raton Basin and other CBM-producing basins in Colorado.

2.0 AVAILABLE DATA AND RESOURCES

This study draws on existing data and studies to provide an overview of conditions in the basin and to provide specific information regarding CBM and water production data. The key datasets reviewed in this study are described below.

2.1 Geographic and Geologic Data

The Raton Basin region's topographic, hydrographic and cultural details were obtained from public domain sources accessible by internet and from geographic information system (GIS) datasets maintained by the U.S. Geological Survey (USGS), CGS, DWR and COGCC. The medium-resolution National Hydrography Datasets for the Arkansas and Canadian river basins, including tributaries present in the Raton Basin, were obtained from the USGS. Coordinates of stream, groundwater, spring and water quality measurement stations were obtained from the USGS National Water Information System (NWIS) online database. Additionally, spatial layers supporting select USGS investigations in the Raton Basin (Watts, 2006a; USGS, 2005) were obtained. The CGS provided geologic cross-sections and generalized stratigraphic sections of the Raton Basin; spatial layers of geology, topography and administrative features, including detailed information for the geologic outcrops of the formations of interest; and, maps displaying this information. Spatial coordinates were obtained for water supply and CBM production wells in the Raton Basin from the DWR and COGCC, respectively, and used in the development of spatial layers of these features.

2.2 Well and Production Data

Oil, gas, and CBM well and production data is systematically collected by the COGCC. Much of their database is available on the internet at http://cogcc.state.co.us. For this study, a project dataset of water and gas production was assembled from pre-1999 lease production and post-1999 well production data obtained from the COGCC. Prior to 1999 the COGCC tabulated water and gas production data for gas leases, so producing formation information is not available for individual wells. Electronic lease data were developed from paper records ('Green Books') maintained by the COGCC. Beginning in 1999, production data, producing formation information, and well completion details are available for individual wells, each with a unique American Petroleum Institute (API) well number. Electronic data for the period from 1986 to

1998 for leases in the Raton Basin were selected from the COGCC database. Lease data include production information from multiple wells, aggregated to a single lease. Electronic data for the period from 1999 to present were selected from the COGCC database for wells screened in the Raton or Vermejo Formations, or, both formations (termed, "commingled"[1]). The primary project dataset used for the stream depletion analysis was assembled from the two COGCC datasets. A process was developed to merge the pre-1999 lease and post-1999 well datasets through the association of lease and well data by facility names; determination of well's activity, such as by the first production date and well completion date; and the assigning of a portion of lease production data to active wells based upon the well's ratio of 1999 production to that of the given lease. The process was applied to leases where well production data is aggregated over a large area.

2.3 <u>Water Level Data</u>

Water level data in the Raton Basin are available from several sources. Water level data maintained by the USGS were obtained from the website http://waterdata.usgs.gov/nwis/gw. Data include discrete measurements from 293 wells, screened in stratigraphic intervals from the Pierre Shale to surficial valley-fill deposits. These data represent water levels from 1949 through 1986. Only six wells in this dataset have more than three water level measurements. Water level data assembled by the USGS for the Watts (2006a) hydrostratigraphic framework investigation were obtained in the form of a geospatial layer from the website http://water.usgs.gov/GIS/metadata/usgswrd/XML/SIR-06-5129_seo_wells_point.xml. This dataset was reported as having been assembled from water supply well completion reports maintained by the Colorado DWR and contains 1,198 discrete measurements of the static water level at the time of well completion, from 1923 to 2002. Additional well information includes screen depth and/or total well depth. Water level data were also obtained directly from the DWR, including 1,674 static water level measurements and well depth information from wells permitted through January 2007 (DWR, 2007). Water level data are also available in USGS investigation reports by Geldon (1989), Geldon and Abbott (1985) and Abbott and others (1983). Geldon (1989) plots high-frequency water-level measurements for 7 wells in the Raton Basin at various temporal scales from as early as 1949 through as late as 1984. Geldon and Abbott

[1] The term "commingled" refers to a well that is reported in the COGCC database as being perforated in both the Raton and Vermejo Formations, and, production data are not separately reported for the contributing formations.

(1985) report water level measurements from 29 relatively shallow wells in various formations, including 16 wells in the Raton Formation, at various monthly or annual-scale periods measured prior to 1983. Abbott and others (1983) report single, discrete water level measurements at 18 water level stations, including 4 mines and 2 springs, from 1949 to 1981. Continuous pressure data from January 1999 to January 2007 in one CBM monitoring well in Huerfano County was provided by the Petroglyph Operating Company. Initial pressure data had been collected by Cedar Ridge LLC in 16 of the CBM wells operated them in northern Las Animas and southern Huerfano counties was obtained from the COGCC. No other operator data has been obtained.

2.4 Stream and Spring Flow Data

Stream and spring flow data maintained by the USGS were obtained from the website http://waterdata.usgs.gov/nwis/. Locations of springs were obtained in digital image format from USGS reports by Geldon (1989) and Abbott and others (1983).

2.5 Water Quality Data

Primary water quality data were not assembled as part of this study; however, existing characterizations of water quality were reviewed. Water quality sampling reports were completed for COGCC by several consultants for input to the COGCC Raton Basin Baseline Study (COGCC, 2003). The ESN Rocky Mountain sampling report contains results for fifty CBM wells in Huerfano and Las Animas counties selected by the COGCC (ESN, 2003). Results include produced water sampled for field parameters, major ion chemistry, trace metals and gas sampled for fixed gas content, hydrocarbon content, carbon and hydrogen isotopes. The Seacrest Group water quality sampling report contains results for water supply wells in Raton Basin (Seacrest, 2003) that were sampled for field parameters, major ion chemistry, dissolved methane, dissolved inorganic carbon, and two stable isotopes. In addition, the COGCC maintains a water quality database of produced water sample analysis results submitted by gas operators or collected by the COGCC.

Water quality data are available from several USGS sources. Water quality data at 107 locations were obtained from the USGS website http://waterdata.usgs.gov/nwis/. Water quality data are primarily derived from groundwater samples and include results for major ion chemistry and metals for the period 1978-2005. Water quality data reported by Geldon (1989) include major ion chemistry in springs and groundwater; trace metal statistics; and, chemical analyses completed for 25 wells, 7 springs and 7 mines in the Raton and Vermejo Formations for the period 1977-1983. Water quality data in Abbott and others (1983) include major ion chemistry at 50 locations for the period 1949-1981.

3.0 PHYSIOGRAPHIC AND GEOLOGIC SETTINGS OF THE RATON BASIN

3.1 Regional Basin Setting

The Raton Basin of southern Colorado and northeastern New Mexico is the southern-most of several coal-bearing basins along the eastern margin of the Rocky Mountains. Coal was first reported in the basin in 1841, when the area was still part of the Mexican Territory. The region contains an estimated 2.7 billion tons of bituminous coal reserves (Geldon, 1989). While active coal mining in the region ceased in the mid-1990s, the region has become one of Colorado's major producers of coalbed methane. Recoverable coalbed methane resources have been estimated as much as 10.2 trillion cubic feet of gas (Stevens and others, 1992); and, more recently at 1.6 trillion cubic feet of gas (USGS, 2005; Higley and others, 2007).

The basin covers an area of about 2,200 square miles extending from southern Colfax County, New Mexico, northward to Huerfano County, Colorado (Figure 3.1). It is bounded by the Culebra Range of the Sangre de Cristo Mountains to the west, the south edge of the Wet Mountains to the north, the Apishapa Arch to the northeast, the Las Animas Uplift to the east, and the Sierra Grande Arch to the south and southeast. The basin is commonly described as an elongate asymmetric syncline that extends 80 miles north to south and as much as 50 miles east to west.

Much of the coal region of the Raton Basin in Colorado coincides with the Park Plateau section of the Great Plains physiographic province (Fenneman, 1931). The Park Plateau is deeply incised by two of the three major drainages in the basin, the Purgatoire and Apishapa Rivers and their tributaries. The Cucharas River north of the Spanish Peaks drains the northern portion of the basin. All three rivers flow east and are tributary to the Arkansas River. Topography ranges from fairly flat along the Cucharas River west of Walsenburg to very steep and rugged in the vicinity of the igneous stocks (Spanish Peaks). The lowest elevation is just over 6,000 feet, along the Purgatoire River west of Trinidad, while the highest elevation occurs at West Spanish Peak (13,626 feet). Most of the Park Plateau ranges in elevation from 6,400 to 8,400 feet. Annual precipitation in the Raton Basin is generally correlative to elevation, ranging from over 30 inches per year in the Spanish Peaks to less than 16 inches per year in eastern portions of the basin. Trinidad and Walsenburg, on the eastern edge of the basin, are the major population centers.

The Raton Basin contains a nearly complete Cretaceous and Tertiary stratigraphic sequence of sedimentary rocks that include the coal-bearing Vermejo and Raton Formations (Close and Dutcher, 1990a) (Figure 3.2). The upper Cretaceous Vermejo Formation and upper Cretaceous and Paleocene Raton Formation overlie the Trinidad Sandstone, a basin-wide regressive marine sandstone (Stevens and others, 1992). The Raton Coal Basin is defined as the outcrop of the Cretaceous Trinidad Sandstone, which encompasses an area of approximately 1,320 square miles in Colorado (Figure 3.1, 3.5). The asymmetric axial trace of the basin coincides with the La Veta Syncline, which parallels and is 5 to 10 miles east of the Sangre de Cristo Mountains. The geologic strata are steeply tilted and faulted along the western margin of the basin. In the deepest part of the basin, which is located approximately 15 miles southwest of Walsenburg, sedimentary rocks that range in age from Pennsylvanian to Eocene may be 20,000 to 25,000 feet thick (Geldon, 1989). Young igneous rocks (early Miocene to recent) form the Spanish Peaks stocks and radiating dikes in the northern portion of the basin along the Huerfano and Las Animas county line. Thinner dikes and sills, of similar composition are scattered throughout the basin.

3.2 Structure and Stratigraphic Setting

The Raton structural basin was part of the larger Rocky Mountain foreland basin and contains sedimentary rocks as old as Devonian overlying Precambrian basement. It evolved into an asymmetric synclinal sedimentary basin during the late Cretaceous-Early Tertiary Laramide Orogeny. Deposition during this orogenic activity resulted in the accumulation of at least 5,250 feet of clastic sediment (Pierre Shale, Trinidad Sandstone, and Vermejo Formations) being deposited along the regressive Western Interior Seaway. The axial trace of the basin represented by the La Veta Syncline results in a steep eastward dip of the sedimentary rocks on the west limb (20-90 degrees), adjacent to the Sangre de Cristo Mountains, and a gentler westward dip (2-10 degrees) on the east limb (Tyler and others, 1991) (Tremain, 1980). Representative cross-sections in the northern and southern portions of the basin are shown as Figures 3.3 and 3.4, respectively. The approximate locations of these lines of section are shown in Figure 3.5. Sedimentary rocks along the western edge of the basin are extensively deformed by steeply dipping thrust faults and several major folds (Hemborg, 1998). The eastern flank of the syncline is only mildly deformed by folding and faulting. Normal faulting within the basin generally displaces strata less than 50 feet (Rice and Finn, 1996). At least 15,500 feet of structural relief exists between the deepest part of the basin and the adjacent Sangre de Cristo uplift.

In the northern part of the basin, the main basinal syncline is bisected by the Greenhorn Anticline (a south plunging spur of the Wet Mountain uplift) (Figure 3.1). The northwest spur is locally known as the Huerfano Park Syncline. Like the La Veta Syncline, it is asymmetrical in form with a steeper western limb (Tremain, 1980). The Delcarbon Syncline trends northeast and dies out against the junction of the Apishapa Arch and the Wet Mountains. This syncline is shallower and more symmetrical (Tremain, 1980). Surface outcrops of the principal coal bearing formations of the Raton Basin are absent just north of the Delcarbon Syncline.

While the Raton Basin has a complex structural and stratigraphic history, its geologic formations are typical of the southern Rocky Mountains. A geologic map of the basin is presented as Figure 3.5. Total sediment thickness is 15,000-25,000 on the western side of the basin and 10,000 feet on the eastern side (Tremain, 1980). A thin Devonian and Mississippian carbonate sequence was deposited in a transgressive marine environment. Uplift of the ancestral Rocky Mountains provided source material for the deposition of terrigenous Permian-Pennsylvanian strata, predominantly silts, sands, and shale. Shallow marine conditions returned to the area during the middle Permian depositing marine sandstones and limestones. The ancestral Rockies were gradually eroded throughout the Mesozoic era (Stevens and others, 1992). The Triassic Dockum Group, consisting of fluvial sandstones with interbedded shale as much as 1,200 feet thick, unconformably overlies the Permian units (Baltz, 1965). The Dockum Group is conformably overlain by several hundred feet of Jurassic strata that consist of continental and shallow-marine sediments. Late Paleozoic and early Mesozoic strata form an eastward thinning wedge 12,000-20,000 thick in the west to 7,000 feet thick in the east (Tremain, 1980).

During the early Cretaceous, the invasion of the Western Interior Seaway dictated the depositional sequence. The Cretaceous section includes 200 feet of the basal clastic sands of the Purgatoire Formation and Dakota Sandstone, followed by 1,000 feet of marine shales, marls, and limestones of the Benton and Niobrara Groups (Hemborg, 1998). The seaway began its final withdrawal from the Raton Basin region during the late Cretaceous in response to the Laramide uplift. At the beginning of this regression, up to 2,300 feet of black, marine Pierre Shale was conformably deposited on the Niobrara. The upper Pierre Shale forms a gradual transition with the overlying and intertonguing Trinidad Sandstone. The marginal marine and partly deltaic Trinidad Sandstone serves as a marker bed in the coal region. The outcrop of the Trinidad Sandstone defines the boundary of the Raton Basin with respect to coalbed methane production. This 0-260 feet thick ledge-forming sandstone is depositionally correlative with the Pictured Cliffs Sandstone in the San Juan Basin and the Fox Hills Sandstone of the Denver Basin. The upper Trinidad intertongues with and is overlain by the coal-bearing Vermejo Formation (Tremain, 1980). The fluvial-deltaic deposits of the Vermejo contain the best developed and most laterally extensive coal beds in the basin. The late Cretaceous and Paleocene Raton Formation, which is also coal bearing, overlies the Vermejo. Clastic sediments shed off the rising Sangre de Cristo Mountains and deposited as a conglomerate mark the erosional contact between the Vermejo and overlying Raton Formation (Stevens and others, 1992). The Tertiary Poison Canyon Formation, consisting of continental terrigenous sediments deposited as the Laramide uplift continued, unconformably overlies the Raton Formation. Up to 10,000 feet of Tertiary sediments were originally deposited in the basin, but erosion has removed much of them (Hemborg, 1998). In the northern part of the basin, the Poison Canyon Formation is overlain by clastic floodplain deposits of the Cuchara, Huerfano, and Farisita Formations. A detailed stratigraphic chart of the Upper Cretaceous and younger sequence is presented as Figure 3.6.

Middle Tertiary and later (Miocene to recent) igneous intrusions are present throughout the basin and cut all of the Cretaceous and younger formations (Figure 3.5). Miocene and Pliocene igneous intrusive rocks of mafic to intermediate composition were emplaced as stocks, laccoliths, plugs, dikes, and sills throughout the coal-bearing Vermejo and Raton Formations (Johnson, 1969). Sills have intruded along coal seams often replacing or upgrading the coal. Two separate dike systems have been identified (Stevens and others, 1992). One set is represented by the hundreds of early Miocene dikes, 2 to 60 feet thick, which radiate from the Spanish Peaks and Dike Mountain. The second set is oriented in an east-west direction perpendicular to the basin axis that intruded pre-existing primary fractures (Tyler and others, 1991). Young (8 to 3.5 million years old) basalt and andesite flows form the Raton Mesas south of Trinidad (Johnson, 1969).

Holocene uplift and erosion removed most of the Middle Tertiary and younger sediments and partially exhumed the Upper Cretaceous Vermejo and Raton Formations (Stevens and others, 1992). Quaternary alluvial deposits have been deposited along the present stream and river drainages.

3.3 Upper Cretaceous/Paleocene Stratigraphy

3.3.1 Trinidad Sandstone

The Trinidad Sandstone serves as the marker bed in the coal region, and its outcrop defines the Raton Coal Basin. The Trinidad Sandstone, ranging in thickness from 0 to 260 feet, is a light gray to buff locally arkosic sandstone with a few thin beds of tan or gray silty shales. Its depositional environment is a prograding marine shoreface. Billingsley (1978) and Manzolillo (1976), divide the Trinidad into an upper fluvial zone and a lower delta-front sandstone.

Stevens and others (1992) divide the Trinidad into three separate units. The basal unit consists of distal offshore bar deposits of a lower delta front environment that include alternating lenses of very fine-grained sand and shale. This sequence is gradational and intertonguing with the underlying Pierre Shale. The middle unit is a fine-grained sand deposit of the lower delta front. Bedding is planar to cross-bedded and moderate to well sorted. The upper part of the Trinidad is a fining upward, medium to fine-grained delta front deposit. It is usually marked by a scour base.

The upper Trinidad intertongues with and is conformably overlain by the coal-bearing Vermejo Formation. The contact is marked by a thick, coal-bearing sequence in most regions of the basin. These stratigraphic relationships are displayed in the type geophysical log from the Spanish Peak field presented in Figure 3.7.

3.3.2 Vermejo Formation

The Vermejo Formation is a 0 to 380 foot thick delta plain deposit consisting of sandstones interbedded with siltstones, shales, and coal. The Vermejo was deposited conformably on the Trinidad Sandstone and includes channel, lagoon, coastal swamp, and delta plain deposits (Stevens and others, 1992). The Vermejo contains the thickest and most laterally extensive coal beds in the Raton Basin. The formation forms gentle slopes or valley floors between sandstones of the underlying Trinidad and overlying Raton Formations.

Tremain (1980) presents a detailed characterization of the individual deposits of the Vermejo Formation. Individual coal beds in the Vermejo Formation range from a few inches to a maximum 14 feet thick. In aggregate, total coal thickness typically ranges from 5 to 35 feet (EPA, 2004). Three main coal-bearing cycles are recorded, with lateral continuity of 1,000 to 3,000 feet (Clarke and Turner, 2002). The contact between the Vermejo and the overlying Raton Formation is characterized by a conglomerate sourced from erosion during uplift of the Sangre de Cristo Mountains. The outcrop area of the Vermejo Formation as presented as in Figure 3.8 is limited to the edges of the basin and areas downcut by the Purgatoire River west of Trinidad.

3.3.3 Raton Formation

The Raton Formation is a 0 to 2,000 foot thick continental alluvial plain deposit consisting of siltstones, sandstones, shales, coal beds, and a basal conglomerate. This lithology is a complex series of channel, overbank, and swamp deposits representing a fluvial meander belt. The Raton Formation contains one of the world's best preserved Cretaceous/Tertiary (K/T) time boundaries (Orth and others, 1981; Pillmore and Flores, 1987). Tschudy and others (1984) and Pillmore and Flores (1984) placed the K/T boundary near the top of the lower coal-rich interval below the sandstone dominated barren series (Figure 3.6). The Raton Formation is exposed over much of the basin (Figure 3.9). Because of extensive erosion, particularly in the eastern part of the basin, much of the original coal is no longer present (Stevens and others, 1992). Tremain (1980) presents a detailed characterization of the individual deposits of the Raton Formation.

Lee (1917) divided the Raton Formation into a basal conglomeratic interval, a lower coal-rich interval, a barren sandstone dominated series, and an upper coal-rich interval (Figure 3.6). The basal conglomerate is as much as 50 feet thick and consists of interbedded pebble conglomerate and granule, quartzose sandstone (Pillmore and Flores, 1987). The lower coal rich zone ranges from 100 to 250 feet thick and is composed of interbedded coal, carbonaceous shale, mudstone, siltstone, and sandstone. The barren series ranges in thickness from 180 to 600 feet. It is dominated by fine-grained sandstones with minor mudstone and siltstone layers and occasional coal beds. The upper coal-rich interval ranges from 600 to 1,100 feet thick, and consists of interbedded sandstone, mudstone, siltstone, coal, and carbonaceous shale (Flores and Bader, 1999).

Total coal thickness in the Raton Formation ranges from 10 to 140 feet, with individual seams ranging from inches to 10 feet (Stevens and others, 1992). The coal seams are characteristically lenticular with lateral continuity of 500 to 1,000 feet (Clarke and Turner, 2002). The distribution of the coals within the Raton Formation is exemplified by the geophysical log presented in Figure 3.10. Although the Raton Formation contains more coal than the Vermejo, individual seams are thinner and less continuous, and they are distributed over 1,200 feet of section. The vertical and lateral variability of the coal seams are characteristic of distal, broad humid alluvial plain environments where peat accumulates in swamps between meandering fluvial channels (Clarke and others, 2004). Between 5 and 15 individual coal seams produce coalbed methane for wells in the basin as well as the methane charged Raton conglomerate (Hemborg, 1998; Carlton, 2006). The Raton Formation grades westward into, and in the north is unconformably overlain by, the conglomeratic Poison Canyon Formation.

3.3.4 Poison Canyon Formation

The Poison Canyon Formation is a 0 to 2,500 foot thick Paleocene age deposit consisting of poorly sorted conglomerates and sandstone interbedded with shales and mudstones. The formation was first described by R.C. Hills in 1891 at Poison Canyon in Huerfano County, Colorado (Tremain, 1980). Because of the similar lithology of the Poison Canyon and Raton Formations, it is often difficult to identify the contact boundary. Typically, the base of the lowest sandstone containing unweathered feldspar grains is chosen as the boundary (Tremain, 1980). The Poison Canyon Formation is exposed over much of the northern portion of the basin. The Poison Canyon Formation is overlain by clastic floodplain deposits of the Cuchara, Huerfano, and Farisita Formations. The Cuchara Formation unconformably overlies the Poison Canyon and consists of up to 5,000 feet massive sandstone interbedded with shale.

3.3.5 Alluvial Deposits

Pleistocene age pediment alluvium, shed from the rising mountains to the west, occurs as erosional remnants overlying the Cuchara and Poison Canyon Formations in the Upper Apishapa River valley. Wood and others (1956) determined that these deposits are generally less than 10 feet thick, but deposits up to 40 feet thick have been documented.

Stream alluvium exists in the valleys of the Purgatoire and Apishapa Rivers and their tributaries. In the Purgatoire River valley, these deposits range from 12-41 feet in thickness (Geldon, 1989). The maximum thickness observed in the Apishapa River valley was 45 feet, with some deposits in associated tributaries reaching 70 feet in thickness (Geldon, 1989). The composition of the stream alluvium takes on the characteristics of the outcropping formation in the area; that is, sand and gravel dominate where canyons are cut into the Poison Canyon and Cuchara Formations, and silt and clay where the Raton or Vermejo Formations dominate.

4.0 COALBED METHANE PRODUCTION

Through 2005, approximately 500 Bcf of CBM gas has been produced from the Raton and Vermejo coals in the Colorado portion of the Raton Basin. The annual gas production history for the Colorado portion of the basin is summarized on Figure 4.1, along with water production. Prior to 1995, there were no gas distribution lines out of the Raton Basin and less than 60 wells had been drilled (Carlton, 2006).

4.1 Raton Basin CBM Gas and Water Production History

Most, if not all, wells in the Raton Basin require hydraulic fracture stimulation to attain economic levels of gas production. Selective hydraulic fracturing procedures are targeted for individual coal seams and to coal seam groups to produce large drainage radii, rapid well interference and accelerated dewatering (Carlton, 2006). The response of gas production to stimulation is varied (Figures 4.2 and 4.3). Gas production peaks immediately after the initiation of production in some wells, and in other wells, gas production peaks several years after initial production. Where depressurizing the formation has been problematic in a few areas of the basin, very large volumes of water have been produced with very little or no methane production.

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. In typical CBM wells, such as those seen in the San Juan Basin, as water production declines, CBM production increases and a well may have a long productive period with relatively high gas production and little to no water production. 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.

The production curves shown in Figures 4.2 and 4.3 illustrate the water/gas relationship for three Vermejo Formation and three Raton Formation CBM wells. Upon completion, Raton Basin CBM wells produce water immediately. In subsequent years, based on examination of records for many wells within the COGCC database, water production continues without significant decline; although, for some wells, water production declines over time. Examination of water production data in the COGCC data base indicates that the average water production per well has not changed dramatically over the period 1999 to 2005 (Table 4.1). During this period, the total number of producing CBM wells increased from 454 to 1,665. The average annual water production is typically about 8 to 10 acre-feet per well.

Figure 4.1 shows total annual water production from Raton Basin CBM wells in Colorado for the period 1986 through 2005. As can be seen, annual CBM water production increased rapidly from 1995 through 2005, increasing to almost 14,000 acre-feet (over 100 million barrels[2]) in 2005. Similar to total annual CBM production for the Raton Basin, the normal gas production curve for a single CBM well generally mirrors water production. Projections for 2006, based on the first six months of the year, indicate that annual production may have reached 85 Bcf of gas and 16,000 acre-feet of water.

The areal distribution of CBM and water production in the Raton Basin in Colorado are illustrated in Figures 4.4 and 4.5, respectively[3]. As shown in Figure 4.4, the majority of the gas production has been within the southern part of the Colorado portion of the basin. In contrast, fields with generally lower gas production have the highest water production, as seen in the Huerfano County portion of the basin (Figure 4.5).

4.2 Well Densities and Distribution

In Las Animas County, north of Highway 12 and the Purgatoire River, much of the Raton Basin is divided into three federal exploration units. In the rest of the Raton Basin, wells are located following the statewide spacing requirements of COGCC Rule 318. CBM development began primarily in the area north of the Purgatoire River and west of the town of Trinidad, Colorado and has spread throughout the Purgatoire River watershed, and in relatively minor amounts to the Apishapa and Cucharas river watersheds to the north. Historically, about 80 percent of CBM production is associated with wells perforated in the Vermejo Formation, about

[2] 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.

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

15 percent in the commingled Raton-Vermejo Formations, with the remainder from the Raton Formation.

4.3 Production Trends and Projections

The trend of future production of CBM gas and water in the Raton 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 combined with the construction of gas distribution lines has spurred the development of production in the Raton Basin. This, combined with the relatively clean burning characteristics of methane gas, suggests that development of CBM in the Raton Basin will continue to occur at a brisk pace for the foreseeable future.

On the basis of continued energy demands and the trend in CBM production in the Raton Basin in Colorado through 2005, it appears that the basin will continue to experience increases in gas and water production. Increases in gas production may come from the development of additional fields, infilling of (adding wells within) existing fields and the enhancement of production in existing wells by techniques such as improved fracture stimulation. Between 1999 and 2005, total gas production from the Vermejo coal has doubled while gas production from the Raton coal has grown by more than an order of magnitude (Figure 4.6). In 2005, production from the Raton and commingled Raton-Vermejo coals accounted for 27 percent of total CBM production in the Colorado portion of the Raton Basin. The USGS estimates that nearly 40 percent of undiscovered coalbed gas in the Colorado and New Mexico portions of the Raton Basin lies within the Raton Formation alone (Higley and others, 2007). Development of CBM resources in the basin is likely at an intermediate stage, with the expectation of continually increasing amounts of CBM gas and water produced from the formation coals.

Current CBM production in the basin is occurring almost entirely in Las Animas County. Development of CBM production in some gas fields in Huerfano County has been hindered by the difficulties in dewatering the formation and it is unknown if technical solutions will prevail or if alternate fields will be developed there. The USGS estimates total undiscovered reserves of CBM in the New Mexico and Colorado portions of the Raton Basin are on the order of 1,600 Bcf

(Higley and others, 2007). The portion of this estimate lying within Colorado is unknown. Assuming that the distribution can be based on proven development areas, approximately 95 percent of proven development areas occur in Colorado, giving a total of 1,520 Bcf. Alternatively, assuming that proven development areas are fully developed, and undiscovered reserves are evenly distributed throughout the rest of the basin, estimated reserves in Colorado would be 675 Bcf.

5.0 HYDROGEOLOGIC CONDITIONS

5.1 Groundwater Flow Systems

Geologic formations within the Raton Basin -- the Poison Canyon, Raton and Vermejo -- include sequences of sedimentary rocks that originated as coastal and alluvial-plain deposits, including siltstones, shales and sandstones, with the latter two formations also containing intervening coal beds. At the land surface, the uppermost sedimentary formation is incised by streams, the Purgatoire, the Apishapa and the Cucharas Rivers, generally flowing from west to east, within narrow alluvial valleys. In some areas, particularly in the northern part of the study area, numerous dikes and sills of volcanic origin are present within the sedimentary formations. Groundwater, generally, flows from recharge areas in the westernmost highlands and the highlands of the Spanish Peaks, towards discharge areas including streams, springs or wells. Groundwater also has been observed to collect in coal mines and is subsequently discharged to streams (Topper and others, 2003; Jacob, personal communication, 2007). Some recharge likely also occurs along formation outcrop areas along basin margins. Locally, groundwater flow may be interrupted or enhanced at the intrusive dikes and sills, depending on their degree of fracturing. Watts (2006a) mapped the "long-term average condition" of the water table, as shown on Figure 5.1. This map reflects depth to water values from water wells less than 250 feet in depth and completed in the uppermost geologic unit. A schematic cross-sectional representation of groundwater recharge and discharge in the central Raton Basin is provided by Geldon (1989) and is shown on Figure 5.2.

While the Poison Canyon, Raton and Vermejo Formations have different depositional histories and variable characteristics within their various units, all tend to be described as consisting of overlapping, gradational sequences, intertonguing, and lacking in laterally extensive correlative units that would be associated with clear and distinct aquifer designations. Regardless, as more data become available, there is some advantage to individually conceptualizing the hydraulic characteristics of the various formations, to permit a better understanding of subsurface flow conditions. This study considers available data in the context of how it has been previously reported. For this reason, the term "aquifer" may be used in discussion to refer to various formations or combinations of formations that produce water.

At the broadest level, the coal-bearing or Cretaceous formations within the Raton Basin can be considered to comprise the Raton-Vermejo-Trinidad aquifer, as described by several authors including, notably, Geldon (1989), and the Colorado Geological Survey, in the *Ground Water Atlas of Colorado* (Topper and others, 2003). More recently, the U.S. Geological Survey completed an investigation to characterize the hydrostratigraphic framework of the basin (Watts, 2006a). A key element of this investigation was subsurface mapping of three hydrostratigraphic units, based on formation designations. Formation top and bottom elevations, and unit thicknesses were identified for postulated hydrostratigraphic units, designated by Watts as the Raton, Vermejo and Trinidad aquifers. However, data were lacking to support characterization of a three-dimensional fluid-pressure regime within these units. Furthermore, Watts notes that additional study is needed to define spatial variability of hydraulic and storage properties within these hydrostratigraphic units, or, aquifers.

5.2 Aquifer Characteristics

5.2.1 Aquifer Extent

Taking the formations within the Raton Basin as a whole, the aquifers relevant to this study may be visualized as lying within the boundary of the Trinidad Sandstone outcrop, as previously shown on Figure 3.5. Within the basin, the Cuchara-Poison Canyon aquifer is largely restricted to the northern portion of the study area where it overlies the Raton Formation. The spatial extent of the Raton and the Vermejo Formations are nearly coincident (Figures 3.3, 3.4, 3.5), but the Vermejo, as the underlying formation, occurs at greater depth than the Raton (Figures 3.3 and 3.4) and only outcrops at the basin margins and along the easternmost reach of the Purgatoire River in the study area. The Raton Formation, on the other hand, outcrops over much of the southern part of the study area and is incised by the Purgatoire River between the western basin margin and, approximately, Trinidad Lake. In addition to the aquifer(s) comprised of the sedimentary rock formations, one may identify localized alluvial aquifers, associated with stream channels dissecting the basin. The alluvial aquifers are limited in extent, are shallow, but contain relatively transmissive sediments associated with recent fluvial deposition.

5.2.2 Water Level Conditions

Figure 5.1 illustrates the long-term average condition for the water table elevation as reflected in wells with depths less than 250 feet below land surface. The potentiometric surface, as identified by Geldon (Geldon, 1989; Topper and others, 2003) for the Cuchara-Poison Canyon aquifer in 1978, is shown on Figure 5.3. The potentiometric surface, as identified by Geldon (Geldon, 1989; Topper and others, 2003) for the Raton-Vermejo-Trinidad aquifer in 1981, is shown on Figure 5.4. These conditions reflect water depths, typically as reported at the time of drilling, for water wells on record with the DWR. The majority of the permitted wells in the Raton Basin are less than 150 feet deep, with 90% of the permitted wells completed at depths less than 450 feet (Topper and others, 2003). Water in the alluvial aquifers adjacent to the streams is typically shallow: Geldon (1989) notes that many hand dug wells exist with depths less than 30 feet. Hydraulic communication between the alluvial material and streams is evidenced by the shallow groundwater levels, gain-loss studies and chemical analyses of groundwater and surface water (Geldon, 1989).

Some, but limited, fluid pressure data for deeper zones of the Raton Basin were available to this study. Data for the Petroglyph field in the Cucharas watershed were used to estimate hydraulic properties for that region (Appendix B); and some data, previously reported to the COGCC, for a group of wells in the Cedar Ridge field in Township 30 South (Appendix C) collected in 2000-2001 were reviewed. While significantly more pressure data may exist, it is not typically found within the public domain.

Several sources suggest that the basin is under-pressured, meaning that hydraulic heads in deep bedrock aquifers are lower than those in shallower formations. For example, this condition is expressed in EPA, 2004, citing Howard (1982), Geldon (1989) and Tyler (1995); and, is reflected in pressure gradient data for wells in the Cedar Ridge field. This condition would suggest that a downward hydraulic gradient exists from the water table to deeper bedrock zones; and, where formation properties permit, downward movement of shallow groundwater to deeper zones may occur.

5.2.3 Permeability

Aquifer parameters have been inferred by two investigators to model impacts of CBM water withdrawals. Martin and Wood (1996) use a hydraulic conductivity of 2.3 feet per day for the combined Raton-Vermejo-Trinidad aquifer in their *Basin Resources Model*, a model developed to support a water rights evaluation in Las Animas County and within the Raton Basin. The value was identified “based on limited published information, some data from the BRI [Basin Resources Inc.] mines, and comparisons with similar hydrogeologic regions (especially the well-known Denver Basin)”; however, no specific data or logic are provided in support of this value. In an assessment of the potential impact of coal bed methane development to public water supplies in the Chicorica Watershed, used for the City of Raton, Balleau (2007) used a transmissivity estimate of 1 foot squared per day, citing the estimates developed by S.S. Papadopulos & Associates, Inc., for the San Juan Basin (2006), and noting (personal communication, 2007) that this value appeared reasonable for the Raton Basin in light of other information that he had reviewed. For this study, rather than adopting parameter values used in previous modeling studies, available well test and other data for the basin were reviewed and used to derive aquifer parameters specific to the Raton Basin.

Geldon and Abbott (1985) provide a comprehensive tabulation of hydraulic characteristic data (transmissivity, hydraulic conductivity and specific capacity) for wells within various aquifers in the Raton Basin, based on specific capacity data reported in the DWR files; and hydraulic tests described in consultant reports and U.S. Geological Survey unpublished data. These data also are summarized in Geldon (1989), and are later summarized in the Ground Water Atlas of Colorado (Topper and others, 2003). Table 5.1 provides a summary of the published hydraulic parameter estimates by aquifer.

For the Raton-Vermejo-Trinidad aquifer Geldon (1989) and Geldon and Abbott (1985) report a combination of permeability estimates, separating them by rock type and type of test. Of 83 tests, the majority of which were “bailing” tests and were located in Las Animas County, a mean transmissivity estimate of 20 feet squared per day is reported. A subset of the tests also provided hydraulic conductivity estimates; a mean hydraulic conductivity of 2.2 feet per day is reported, with a median value of about 0.12 feet per day, for 26 tests. One of the 26 tests, for a 2-foot interval of fractured siltstone, yielded a hydraulic conductivity of 45 feet per day (Geldon and Abbott, 1985). This value reflects the enhanced permeability that is encountered where the formation is fractured. Excluding this value which reflects secondary rather than matrix conductivity, a mean hydraulic conductivity of 0.49 feet per day is obtained for the remaining 25 tests. However, it is not known to what extent fracturing impacts the overall effective average permeability of the formation given the number and type of reported tests. The tested thickness, where noted for 15 tests, ranged from 2 feet to 220 feet, with a median value of 34 feet. Because the tested thickness is considerably less than the formation thickness, and because most of the tests were of short duration, the test-derived values for hydraulic conductivity may be better suited for characterization of the formation properties than the reported transmissivities.

Geldon (1989) also presents test results according to rock type for 25 of the tests; these tests correspond to those for which a rock type specification appears to have been available in source reports (Geldon and Abbott, 1985). Among these tests, 11 represent sandstone, 6 represent coal, 2 represent siltstone, and 6 are designated as mixed. The mean hydraulic conductivity was 0.35 feet per day for the 11 sandstone tests, and was 1.1 feet per day for the 6 coal tests. The number of samples for siltstone prohibits a meaningful comparison for siltstone. Geldon (1989) notes that coal and sandstone comprise about 29 percent of the Raton-Vermejo Formations. Other indications that the coal permeability is sufficient to transmit water include the magnitude of water production from coal mine shafts[4]. Among these, Geldon (1989) describes the Allen Mine as having an average discharge of 73 gpm; the Maxwell mine as having an average discharge of 15 gpm; and, the Frederick mine as discharging 31 to 37 gpm.

Considering the above information, a hydraulic conductivity value of 0.5 feet per day may be considered reasonable for the sandstone and coal intervals within the Raton and Vermejo Formations in Las Animas County. Assuming that most of the formation transmissivity occurs within the sandstone and coal intervals, or within approximately 29% of the formation thickness (Geldon, 1989), one may approximate a formation transmissivity by applying that percentage to the separate formation thicknesses inferred to be saturated. Watts (2006a) has mapped formation thicknesses based on examination of well logs. The Raton Formation thickness varies across the basin, with minimal thickness along basin margins and thickness in the range of 800 to 1,200 feet

[4] Data regarding the water level gradient and mine surface area associated with these flows were not found; thus, these data were not able to be used to estimate specific permeability values.

over much of the basin interior. However, particularly in the upland areas, where depths to water can be greater than several hundred feet, the formation thickness is significantly greater than the *saturated* formation thickness that is used to estimate transmissivity. For purposes of estimating transmissivity for a simplified stream depletion analysis, a saturated thickness estimate of about 400 feet is reasonable, considering mapped formation thicknesses and depth to water data; and, considering conditions in areas approaching stream discharge and outcrop areas that will tend to exert greater influence on the stream depletion impacts. The mapped thickness of the Vermejo Formation (Watts, 2006) is less variable than that for the Raton Formation, with thickness over much of the basin in the range of 250 to 350 feet. For purposes of estimating transmissivity for a simplified stream depletion analysis, a saturated thickness estimate on the order of 300 feet is reasonable for the Vermejo Formation. Assuming an effective average formation saturated thickness of 400 feet and 300 feet, respectively, for the Raton and Vermejo Formations, and applying Geldon's estimate for percentage sandstone and coal within the Formations, one may estimate an effective average transmissivity of 60 feet squared per day for the Raton Formation, and 45 feet squared per day for the Vermejo Formation in Las Animas County.

Little published data were available for characterization of permeability in Huerfano County. Watts (2006a) excluded Huerfano County from his hydrostratigraphic framework report, noting the presence of fewer CBM wells and a lack of information in this area. Geldon (1989) did not include any aquifer tests for Huerfano County in his report. Examination of CBM production data for both gas and water (Figures 4.4 and 4.5) suggest that the Raton and Vermejo Formations are different in these two regions. Water production is significantly greater for wells in Huerfano County than for wells in Las Animas County, suggesting a higher transmissivity than is characteristic in Las Animas County. Geologic maps of volcanic intrusions indicate a higher density of intrusive dikes and sills in Huerfano County, which may contribute to a higher degree of fracturing and could explain the apparent higher transmissivity. Petroglyph Operating Company (2007) provided some fluid pressure data at one monitoring well in their field, and associated production data from over 50 wells. These data also appeared to reflect a higher transmissivity, potentially influenced by fractures. The monthly production and pressure data were analyzed for a five-year period (1999 to 2004) to estimate formation properties. Described in Appendix B, this analysis yielded a transmissivity estimate of 230 feet squared per day for this region of Huerfano County.

Finally, it is noted that many producers stimulate coal seams with hydraulic fracturing treatments (EPA, 2004). Induced fractures also may increase unwanted water production from associated sandstones, sills or water-bearing faults within the Raton or Vermejo Formations; or, may create connections to the Trinidad Formation (EPA, 2004). In summary, the induced fracturing will locally increase formation permeability and may expand the network of flow paths towards more permeable formations.

5.2.4 Storage Properties

Several parameters are used to describe storage properties in aquifers. These include porosity, specific storage, storage coefficient (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.

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 termed storage coefficient (storativity), or, 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). The USGS (Lohmann, 1972) provides a generalization that the storage coefficient (i.e., storativity) of most confined aquifers is about 10^{-6} per foot of aquifer thickness.

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 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.

Little data are available for quantification of storage properties in Las Animas County. Geldon (1989) reports a value of 0.04 for the specific yield of alluvial aquifers. While not reporting specific test data for the underlying bedrock aquifers, he assumes a value of 0.0004 for the Cuchara-Poison Canyon aquifer based on the stratigraphic equivalence to the Dawson aquifer of the Denver Basin; and, similarly, he assumes a value of 0.0003 for the Raton-Vermejo-Trinidad aquifer based on stratigraphic equivalence to the Denver, Arapahoe and Laramie-Fox Hills aquifers. Balleau (2006) used a storage coefficient of 0.003 in his analysis for the Chicorica Watershed, based on a general comparison of this aquifer to conditions in the San Juan Basin and other factors. Martin and Wood (1996) adopted a specific yield of 0.05 for their model of the Raton Basin aquifer (described as the Raton-Vermijo-Trinidad aquifer); they did not provide or comment on representative values for storage coefficient.

Water table conditions will exist in the uppermost regions of the Raton Basin aquifers, for example, in the Cuchara-Poison Canyon Formation in the northern part of the basin and in the uppermost saturated portion of the Raton Formation of the southern part of the basin. However, given the heterogeneity of formations in the Raton Basin, and the presence of interspersed fine grained materials, confined or semi-confined conditions will occur throughout much of the formations, including the Raton Formation, except at its uppermost extent. Pressure effects from pumping CBM wells in the Raton and Vermejo Formations are expected to propagate generally in a confined fashion until the upper, or water-table, interval is reached, at which point, the pressure effects will also, in most circumstances, reach locations at or near the incised stream channels. For this reason, the application of a confined, or semi-confined, value for storage coefficient is reasonable for estimation of stream depletion from CBM produced water, under the simplified methodology applied in this study. For the Vermejo Formation, following a rule-of-thumb for estimation of storage coefficient (Lohman, 1972, p. 53), using a specific storage of 1×10^{-6} ft^{-1} and assumed saturated thickness of 300 feet, a storage coefficient of 3×10^{-4} is estimated. Similarly, one might calculate a storage coefficient of 4×10^{-4} for the Raton Formation; however, producing zones within the Raton Formation likely behave in a semi-confined rather than fully confined fashion due to the closer proximity of producing coal beds to the water table and consequent opportunity for diminished drawdown. For this reason, a storage coefficient on the order of 4×10^{-3} is considered reasonable for the Raton Formation.

Analysis of production and fluid pressure data for the Petroglyph well field in Huerfano County yielded a storage coefficient of 2 x 10^{-3}, associated with the transmissivity noted previously of 230 feet squared per day (Appendix B).

5.2.5 Stream-Aquifer Contact, Recharge and Discharge Areas

Several streams and tributaries pass through the study area, bringing surface water into contact with the shallow alluvial and underlying bedrock aquifers. The stream-aquifer contacts are best seen by examination of Figure 3.5; these contact areas are briefly described below for the Cucharas River, the Apishapa River and the Purgatoire River. Discharge locations, represented by springs and seeps, are mapped on Figure 5.5.

5.2.5.1 Cucharas River Watershed

The Cucharas River flows year-round through the northern part of the study area. In the vicinity of La Veta, the river contacts the Cuchara Formation; further east, it contacts the Poison Canyon Formations. At the eastern edge of the basin, in the vicinity of Walsenburg, the Cucharas River intersects outcrops of the Raton Formation, the Vermejo Formation and the Trinidad Sandstone.

The average annual discharge in the Cucharas River at Boyd Ranch, near La Veta (USGS station 07114000, drainage area of 56 square miles) ranged from less than 10 cfs to more than 50 cfs between 1935 and 1981 (USGS NWIS search, May 2007), with values typically in the 20 to 40 cfs range. Over the 47-year period of record, winter daily mean flows (November through mid-March) are typically 7 to 8 cfs; daily mean flows in the run-off season, May through July, fall within the range of 30 to 80 cfs; and daily mean flows for the intervening months are typically in the range of 10 to 20 cfs.

Numerous shallow wells are present in this watershed; well yields for the Cuchara-Poison Canyon aquifer are reported in the range of less than 1 to 33 gpm (Topper and others, 2003; DWR, 2007). Reported transmissivities are variable, reflecting the formation heterogeneity (Table 5.1). Both the Cuchara-Poison Canyon and the Raton aquifers contain some shale within the sandstone and conglomerate. The less transmissive horizons will provide some vertical resistance to flow, and may influence discharge via springs in some locations. The aquifers in this area may be recharged by infiltration of precipitation, by streamflow, or by flow from adjacent formations. Discharge may occur as springflow and as stream baseflow, in addition to flow to wells or coal mines. Whether vertical flow occurs in an upward or downward direction is a function of pressure gradients, which are not well-characterized in this region.

5.2.5.2 Apishapa River Watershed

The Apishapa River runs, generally from west to east, through the central portion of the study area, in the northern part of Las Animas County, draining an area of 126 square miles upstream of Aguilar (station 07118000). The Apishapa River flows across the Poison Canyon Formation through ranges 67 and 66 west, then flows across the Raton Formation until it reaches the Vermejo Formation outcrop, in the vicinity of the town of Aguilar. Average annual discharge records available for the Apishapa River near Aguilar (station 07118000) from the USGS NWIS database (May, 2007) show a range of average annual discharge between 1 and 46 cfs for the years 1940 to 1950, with a median of about 10 cfs. Daily records from a nearby station (07118500) monitored in 1978 to 1981 indicate that except during peak runoff months, which may include spring or summer months, daily flows are relatively low, i.e., dry to 1 cfs. Flows above 50 cfs occurred through a 70-day period in May-June of 1980, and sporadically in August of 1981. While the flow at the Aguilar gage may be reduced by diversions during the irrigation season, the winter flows, reflecting base flow, are not affected by upstream diversions. The dry to very low flow conditions reflected in the daily record for the non-irrigation season indicate that the Apishapa River receives little to no base flow (aquifer discharge) in the reach upstream of Aguilar. However, during the run-off season, the Apishapa River may provide some opportunity for aquifer recharge through the channel alluvium. As such, the Apishapa River is not considered a significant receptor for stream depletion impacts from CBM wells.

5.2.5.3 Purgatoire River Watershed

The Purgatoire River flows from west to east, generally in Township 33 South, in the southern portion of the study area. The Purgatoire River exits the Raton Basin as defined for this study in the vicinity of Trinidad, where it crosses the outcrop of the Vermejo Formation. Through most of this area, the river channel alluvium directly overlies the Raton Formation.

Two gaging stations have been monitored by the USGS along the Purgatoire River in the study area. The Middle Fork Purgatoire River at Stonewall (station 07712450) is located on the western margin of the study area, and drains 52 square miles. This station was monitored from May 1978 to September 1981. Daily discharge records from this period indicate that the river flows perennially where it enters the Raton Basin at Stonewall. Winter baseflows, reflected in the daily discharge data, appear to range generally between 4 and 8 cfs. Flows increase in the late spring through the mid-summer with mean daily flows generally in the range of 20 to 100 cfs during the run-off season. The Purgatoire River is also gaged near Madrid, about one mile downstream from Burro Canyon, upstream of Trinidad Lake (Purgatoire River at Madrid, station 07124200). This station reflects a drainage area of 550 square miles and has been gaged since 1972. The mean annual discharge over this 34-year period of record is about 75 cfs; over the 1978 to 1981 period, daily mean discharges during the late summer, fall and winter months typically are within the 10 to 20 cfs range and during the run-off season typically fall in the 100 to 300 cfs range

Hydraulic communication between the near-surface horizons of the Raton Formation and the Purgatoire River is evidenced by a number of factors, including the perennial flow in the river, the presence of shallow groundwater, and the existence of numerous springs in the vicinity of the river (Figure 5.5). Hydraulic communication with deeper horizons may be impeded to some degree by the presence of shales that cause vertical resistance to flow. However, because none of the shales are regionally continuous, they are not likely to prevent some degree of hydraulic communication between deeper horizons and the river. Similarly, hydraulic communication with the deeper Vermejo Formation is not clearly precluded by the documented lithology. However, if the effective average vertical hydraulic conductivity is sufficiently low, stream depletion from water production in the Vermejo Formation may impact the Purgatoire River where it flows across the Vermejo Formation outcrop with little impact to the reach flowing across the overlying Raton Formation.

5.2.6 Potential Stream Depletions

Based on evaluation of lithologic characteristic, streamflow conditions, shallow groundwater elevations, presence of springs, and other information discussed in the previous sections of this report, stream depletion from water production by CBM wells may potentially occur to the Cucharas River and the Purgatoire River within the Raton Basin. Stream depletion to the Apishapa River is considered unlikely, or, insignificant, due to its intermittent flow characteristics, as discussed in Section 5.2.5.2.

The timing and location of stream depletion impacts to the Cucharas River and the Purgatoire River will be addressed for each of the Raton and Vermejo Formations. The elevation of the top of perforated intervals for the CBM wells in the Raton and Vermejo Formations are shown on Figures 5.6 and 5.7, based on information provided in the COGCC database. This information will be considered in structuring the stream depletion analysis. Factors influencing stream depletion include distance from the pumping horizon to the stream, the horizontal and vertical hydraulic conductivity within the intervening formation(s), as well as the storage properties of the intervening formation(s). The stream depletion analysis is described in Section 6.

5.3 Groundwater Chemistry

Drawing from chemical analyses of groundwater from 70 sites, Geldon (1989) notes that the average composition of groundwater in individual aquifers is distinctive. The alluvium is characterized as a calcium bicarbonate water; and the Raton-Vermejo-Trinidad is sodium bicarbonate. Geldon notes an average total dissolved solids concentration (TDS) of 463 mg/L from 20 alluvial groundwater samples, ranging from 200 to 1,000 mg/L. Samples reviewed by Geldon in the Raton-Vermejo-Trinidad aquifer ranged from 300 to 1,500 mg/L of TDS. Mapped total dissolved solids concentration within the Raton-Vermejo-Trinidad aquifer from samples obtained at depths of less than 350 feet (Topper and others, 2003) indicate increasing concentrations along the flow paths, with concentrations varying from 500 in upland areas to concentrations exceeding 1,500 mg/L along the discharge areas in the eastern part of the basin, near Trinidad Lake. Geldon (1989) notes that the concentration of ions increases with depth and higher concentrations are observed in mining effluent. For example, the average sulfate concentration from seven samples collected from mine shafts in the early 1980s was 440 mg/L.

Between 2000 and 2003, the COGCC conducted the Raton Basin Baseline Study to document existing conditions, including data regarding water quality (http://www.oil-gas.state.co.us/Library/RatonBasinReports.htm). As part of that study, water quality analyses were made of samples collected from a large number of water wells and produced water from CBM wells. Approximately 100 private water sources were tested for a suite of inorganic and organic parameters (Seacrest, 2003); and, 50 CBM wells were sampled for pH, anions, cations, total dissolved solids and selected metals (ESN Rocky Mountain, 2003).

Analyses of water well samples (Seacrest, 2003) reflect high variability. The mean TDS was 565 mg/L and most of the high TDS levels were due to the presence of bicarbonate; additionally, some wells evidenced high levels of sulfate. The variability in parameters likely reflects both localized conditions and differences in flow paths from recharge sources to the wells.

The ESN Rocky Mountain report (2003) on produced gas and water testing of CBM gas wells provides maps illustrating concentrations of anions, cations, TDS and other parameters, as well as a tabulation of analytical results, for each of 50 wells. For wells in the Purgatoire watershed, TDS concentrations in CBM produced water tend to fall in the range of 2,000 to 7,000 mg/L, with a few exceptions at higher levels to the south, and several with TDS concentrations in the range of 1,000 to 2,000 to the east, near the recharge areas. For wells in the Cucharas watershed, TDS concentrations are much lower, clustering around 1,000 mg/L for five wells tested in that area. A weighted average of produced water concentrations provided by Petroglyph, operating in this region, indicates a total dissolved concentration of 733 mg/L. These results suggest a more active flow regime, or, greater proximity to recharge sources, in the northern portion of the basin.

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 Raton Basin, specifically, the Cucharas River and the Purgatoire River. 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 Raton Basin.

Pursuant to C.R.S. 37-90-103(10.5) and 37-92-103(11) non-tributary groundwater is defined as groundwater withdrawn from a well which 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. 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*[5] 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 decreed or vested water rights. In most cases, augmentation of depletions to streams will be required. Because of the potential for water

5 "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.)

withdrawn from the CBM wells in the Raton Basin in Colorado to be tributary to the streams that cross the aquifer and because these streams, tributary to the Arkansas River, 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 rate within 100 years of pumping (or, a stream depletion ratio of 0.001).

6.1 Glover Depletion Analysis

DWR has specified that the methodology applied to the depletion analyses in this study will be the analytical "Glover" (or "Glover-Balmer") methodology (Glover and Balmer, 1954). The Glover methodology is premised on a number of simplifying assumptions that require careful attention to problem set-up and parameterization. The method and its application to the Raton Basin are described in this section.

6.1.1 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 (stream depletion ratio) 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 in a number of stream-connected basins of the western United States.

6.1.2 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, the imprecision associated with divergence from the ideal case is often acceptable in basin-scale application. For this stream depletion analysis, where the model is being applied over a large region and impacts are evaluated over a long time frame, many of the method's limitations are not problematic, particularly for the purpose of providing a first-order estimate of stream depletion. The idealizations inherent in the Glover analysis and comments regarding the application of the method to the Raton Basin are provided below:

- *The aquifer is homogeneous*. As described in Section 3, as reflected in well tests, and as depicted schematically in Figure 5.2, the aquifers in the Raton Basin are heterogeneous with materials of various lithologic descriptions, and in some areas, these materials are dissected by dikes and sills. Groundwater movement through a heterogeneous aquifer can be modeled as flow in a homogeneous media through the identification of "effective average parameters" that, on the scale of the problem to be solved, will reasonably characterize the aggregate properties of composite materials. Effective average parameters, ideally, are determined through examination of system-scale stress-response data, for example, wellfield production and fluid pressure data. Where such operational data are not available, best estimates must be developed from localized or site-specific test data. Both of these methods are applied in this study to derive best-estimate hydraulic parameters that will reasonably incorporate the heterogeneity known to exist in the Raton Basin.

- *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 physical configuration of the basin. With respect to the stream location, the key element is identification of the nearest stream location that intersects the modeled formation (for the Raton Basin application, this is more fully discussed in Section 6.1.3). Regarding the assumption of a fully penetrating stream, the fundamental element of the assumption is that hydraulic communication between the producing interval of the formation and the stream is not impeded beyond what is implied by the aquifer hydraulic properties. At the scale of this application, this approximation is not problematic. For example, most wells are located thousands of feet away from the stream boundary. At these distances, whether or not the stream fully penetrates the modeled formation has little bearing on the calculated depletion. This assumption has been evaluated quantitatively by several investigators: McWhorter and Sunada (1981) suggest that partial penetration of a well is not important when considering impacts at a distance of more than 1.5 times the aquifer thickness; Hantush (1965) examines the impact of varying degrees of semi-pervious stream beds on calculated stream depletion with simplified methods. Using relationships developed by Hantush, one can see that the impact of a semi-pervious stream bed, for example, a stream bed with a hydraulic conductivity 1000 times lower than the horizontal hydraulic conductivity of the aquifer, will not substantially impact calculated stream depletions for wells at distances more than a half mile from the stream. Furthermore, at large times, i.e., more than 10 years, the calculated stream impacts become relatively insensitive to assumptions regarding the permeability of the stream bed, regardless of distance.

- *Flow within the modeled aquifer is horizontal.* On a regional scale, wherein most wells are located at distances many times the thickness of the aquifer, the flow can be treated as horizontal without introducing significant error. The violation of this assumption at wells located very close to the stream will result in some over-estimation of stream depletion impacts particularly in early years. However, the overall results of this study are not sensitive to this approximation.

- *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. For the Raton Basin, the presence of flowing gas will have the effect of reducing permeability in the vicinity of the producing well. However, it is unlikely that quantities of gas would be sufficient to affect the overall permeability on the regional scale. The calculation of stream depletion impacts will be driven largely by effective average regional parameters rather than by transient, localized, permeability changes in the vicinity of a CBM production well.

6.1.3 Geometry and Problem Configuration

Based on evaluation of lithologic characteristics, streamflow conditions, shallow groundwater elevations, presence of springs, and other information discussed in the previous sections of this report, stream depletion from water production by CBM wells may potentially occur to the Cucharas River and the Purgatoire River within the Raton Basin. Because little to no winter base flow is present in the Apishapa River, this river is not considered to be significantly affected by stream depletions and is not explicitly modeled in this study[6]. The timing and location of stream depletion impacts to the Cucharas River and the Purgatoire River will be a function of distance from the pumping horizon to the stream and of the transmissive and storage properties of the intervening formation materials. The problem configuration with

[6] If, contrary to this assumption, some hydraulic connection exists and a small amount of stream depletion does occur at the Apishapa River, these amounts will be reflected in the overall amounts calculated for the Purgatoire River, albeit with some timing offset. Regardless, the overall results of this study will not be sensitive to this assumption.

respect to geometry is as described below. Assumptions regarding the formation hydraulic properties are identified in Section 6.1.4.

Impacts to Cucharas River: The producing formations are not generally present at land surface in the immediate vicinity of the CBM wells in the Cucharas watershed. The assumed distance from a well to the potentially impacted stream will be taken as the distance to the stream where it transects the outcrop of the producing formation[7]. This approach neglects the potential for impacts to propagate vertically through overlying formations, but assumes that reasonable hydraulic connection occurs within a formation to the outcrop of that formation where it is traversed by a stream. Dikes that may be present in this area are not explicitly modeled for the following reasons. First, dikes may function to impede or enhance flow where they are present; however, information regarding the function of specific dikes is not available. Second, the dikes tend to be located south of the major water producing production areas and are thus not likely to have a significant bearing on the calculated impacts.

Impacts to the Purgatoire River: The Raton Formation outcrops through much of this watershed, and is traversed by the Purgatoire River. Production intervals are not situated at great depths below the river elevation, and there is no evidence that widespread, continuous, geologic barriers exist that would prohibit the propagation of stress from the production interval to the river. Therefore, the distance to the river from Raton production wells will be taken as the shortest distance from the production well to Purgatoire River, where it crosses the Raton Formation. Similar to the Cucharas River, the distance to the river from Vermejo production wells will be taken as the shortest distance from the production well to the Purgatoire River, where it crosses the outcrop of the Vermejo Formation. As assumed for the Cucharas River, this approach neglects the potential for impacts to propagate vertically through overlying formations, but assumes that reasonable hydraulic connection occurs within a formation to the outcrop of that formation where it is traversed by a stream.

[7] The "stream" in the calculation is a linear feature located at a distance equal to the distance from the well to the outcrop. This approximation lumps impacts to the stream with nearby outcrop impacts, which will, in turn, impact the stream with some lagged effect.

6.1.4 Parameter Estimation and Water Production Volumes

For the Cucharas watershed, in the northern part of the study area, a transmissivity of 230 feet squared per day and a storage coefficient of 2 x 10^{-3} is applied for estimation of stream depletion from CBM-produced water from the Raton-Vermejo combined and the Vermejo Formations. The estimated value of transmissivity reflects the inferred higher permeability of the formations in this region, supported by the high rates of water production observed by producers in this area, and is consistent with the pressure data reported by Petroglyph (Appendix B). The apparent higher transmissivity, potentially influenced by fracturing, may also be associated with better hydraulic communication with upper horizons, resulting in a semi-confined parameter value for storage coefficient.

The water production volumes for wells in the Cucharas watershed were derived from the COGCC database. Produced water was tabulated separately for wells identified as producing primarily from the Raton-Vermejo, or, “combined” formations, and those identified as producing the majority of water from the Vermejo Formation (Groups 1 and 2, Table 6.1). However, the analysis conducted in Appendix B reflects the aquifer response due to pumping from both sets of wells and no information is available to this study to support differentiation of hydraulic properties among these well groups. Therefore, for the depletion analysis, one set of aquifer parameters developed for the “combined” and Vermejo Formations are used for all wells in the Cucharas watershed (Table 6.2).

Detailed pressure data from monitoring or production wells, as would be required to develop basin-wide or regional parameter estimates through a calibration process, were not available for the Las Animas County portion of the study area, which, generally, corresponds with the Purgatoire watershed. Therefore, this analysis makes assumptions based on published aquifer test values and qualitative determinations as are supported by the data that have been reviewed.

For the Purgatoire watershed, in the southern part of the study area, a transmissivity of 60 feet squared per day and a storage coefficient of 4 x 10^{-3} is applied for estimation of stream depletion from CBM-produced water from the Raton Formation. A transmissivity of 45 feet squared per day and a storage coefficient of 3 x 10^{-4} is applied for estimation of stream depletion from CBM-produced water from the Vermejo Formation. These values are based on reported test values and related formation characteristics, as described in Section 5 of this report. The water production volumes for two sets of wells within the Purgatoire watershed (Group 3 and 4) are identified on Table 6.1. The aquifer parameters are noted on Table 6.2.

The assumptions for both watersheds involve both inference and simplifications of actual aquifer boundaries and hydraulic parameters. The calculations are intended to provide a general approximation of stream depletions as a framework for agencies to consider which portions of the basin are tributary or non-tributary. Should a more definitive analysis be desired, parameter estimates and stream depletion estimates can be refined if additional pressure data are acquired.

6.2 Results of Glover Stream Depletion Analysis

6.2.1 Characterization of Percentage Depletions

Figure 6.1 shows the locations of wells as they were grouped for the stream depletion analysis. Figures 6.2 and 6.3 indicate the distance calculated from each well to the stream where it traverses the outcrop corresponding to the pumping interval of the CBM well. For the Cucharas watershed, as discussed previously, the stream depletion analysis was applied to all wells assuming the same formation properties. The distance is computed to the approximate intersection of the Raton and Vermejo outcrops with the Cucharas River. For the Purgatoire watershed, the stream depletion analysis was separately conducted for wells with the majority of production reported for either the Raton or Vermejo Formations.

6.2.2 Current and Projected Future Depletions

Figures 6.4 and 6.5 show the rate of stream depletion as calculated assuming:

- Historical production rates from 1999 to 2006;
- Continuation of 2006 pumping rates through 2099; and,
- Continuation of 2006 pumping rates through 2018, followed by no pumping from 2019 through 2099.

These calculations reflect the aggregate stream depletion, by each of the four well groups, based on each well’s location and a monthly production schedule. The stream depletion analysis indicates that the present magnitude of stream depletion from all wells producing in the Colorado portion of the Raton Basin is approximately 2,500 acre-feet per year.

Figures 6.6 shows the fraction of pumping from the Raton-Vermejo combined Formations and the Vermejo Formation that is projected to impact the Cucharas River at the outcrop with the Raton and Vermejo Formation after a period of 100 years. While it is unlikely that CBM wells would be productive for anywhere near this length of time, the 100-year analysis was requested by the DWR to provide an analysis consistent with their customary methodology for considering impacts of stream depletion.

Similarly, Figures 6.7 and 6.8 show the fraction of pumping (stream depletion ratio) from the Raton, and Vermejo Formations, respectively, that would impact the Purgatoire River in Las Animas County, after a period of 100 years. In all cases, there is no existing well location in either watershed that is not projected to impact the associated stream by at least one tenth of one percent (above a stream depletion ratio of 0.001) under the assumption of 100 years of pumping.

6.2.3 Sensitivity Analysis

The projected depletions are based on best-estimate average aquifer parameters developed as described above. A sensitivity analysis was undertaken to examine the sensitivity of the results to the assumed transmissivity and storativity values. For the sensitivity analysis, the Glover-Balmer equation was back-solved for the distance at which a stream depletion ratio of 0.001 would result in 100 years (the non-tributary criterion) for varying parameter combinations.

For the Raton Formation in the Purgatoire watershed, nearly all wells are located within 12 miles of the Purgatoire River where it intersects the formation (Figure 6.2). The sensitivity analysis indicates that if the transmissivity is reduced by a factor of three and the storativity is unchanged, the non-tributary line would lie at a distance of about 12 miles from the river, and all wells would remain classified as tributary; alternatively, if the transmissivity were unchanged and storativity was increased to 0.01 (a reasonable specific yield for fracture-based storage, although would neglect the semi-confined behavior expected for this formation), the non-tributary line would lie at 13 miles from the river and all wells would remain classified as tributary.

Similarly, for the Vermejo Formation in the Purgatoire watershed, nearly all wells are located within 20 miles of the Vermejo outcrop west of Trinidad Lake (Figure 6.3). The sensitivity analysis indicates that if transmissivity were reduced by a factor of 10 from the assumed value and storativity was unchanged, the non-tributary line would lie at a distance of about 20 miles from the outcrop west of Trinidad Lake, and all wells would remain classified as tributary; alternatively, if the transmissivity were unchanged and the storativity was increased by a factor of 10, the non-tributary line would lie at a distance of about 20 miles from the outcrop west of Trinidad Lake and all wells would remain classified as tributary. If transmissivity is reduced by a factor of four and storativity is doubled, a similar conclusion is reached.

For the "combined" formations in the Cucharas watershed nearly all wells are located within 15 miles of the stream where it transverses the outcrop (Figures 6.2 and 6.3). The sensitivity analysis indicates that if transmissivity were reduced by a factor of 10 from the assumed value and storativity was unchanged, the non-tributary line would lie beyond 15 miles from the outcrop and all wells would remain classified as tributary; alternatively, if the transmissivity were unchanged and storativity was increased to 0.01 (a reasonable specific yield for fracture-based storage, though would neglect the semi-confined behavior expected for this formation), the non-tributary line would lie beyond 20 miles from the outcrop and all wells would remain classified as tributary.

6.3 Suitability of the Glover Method

It is recognized that the Raton Basin is a complex, heterogeneous hydrogeologic setting, involving structural features, volcanic features and a variety of stratigraphic units. The application of the Glover Method requires that complex features be generalized into a simple conceptual model. Such generalizations, applied to even a simple basin, ignore details in time and space that will have bearing on the resulting calculations. Regardless, there is merit to application of a simplified model for reasons of administrative simplicity, for initial problem assessment, and/or when data necessary for a more detailed modeling approach are lacking.

Based on review of data and analyses provided in the previous sections, the Glover Method is considered suitable for providing a preliminary assessment of stream depletion associated with water production from coal bed methane wells in the Raton Basin. On a basin-wide scale, for broad assessment purposes, many of the limitations of the Glover method are not problematic. Furthermore, given that the Glover method is widely used by the DNR and simple to apply, as a regulatory tool, this method seems appropriate for application, particularly in the absence of a more complex approach. Data is not presently available in the public domain to provide sufficient detail to significantly improve on the reliability/precision offered by the Glover analytical model. The application of the Glover method provides a means of approximating the overall scale of potential stream depletion associated with coal bed methane water production.

On the other hand, generalizing assumptions required for the Glover method could be handled differently in the context of a numerical model, if suitable data were available to construct a spatially distributed model. If additional data can be acquired or developed, in particular, pressure data at a large number of production and monitoring wells, then, a spatially distributed numerical model could be used to refine the stream depletion impacts as calculated herein. Based on the review of available data and the sensitivity analysis, it is considered unlikely that a more complex model would change the study conclusion regarding the area identified as meeting the DNR tributary criteria. However, should additional data be available to justify the effort in building a more complex model, it is likely that such a model will compute differing rates and magnitudes of stream depletion, with differences potentially important if a regulatory requirement for offsets were in place.

7.0 RATON 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 Colorado Revised Statutes and DWR regulations or if it is discharged under CDPS permit issued by the Colorado Department of Public Health and Environment – Water Quality Control Division. 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)[8]. The regulatory framework may appear complicated, but the authority and guidance to put CBM water to beneficial use are well established. In the Raton Basin CBM produced water is disposed via several methods including injection wells, produced water pits and discharge to streams.

[8] "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. All CBM produced water in the Raton Basin has a TDS of less than 10,000 mg/L, the water quality criterion for designation of an underground source of drinking water. Much of the produced water has significantly lower TDS concentrations, i.e., less than 3,000 mg/L and may be suitable for livestock watering or irrigation. As such, there is not an immediate reason to discount the potential use of CBM produced waters in the Raton Basin for beneficial uses.

7.3 Interstate Stream Compact Considerations

The U.S. Supreme Court continues to work on the settlement of Kansas v. Colorado, where the State of Kansas has sued the State of Colorado for damages caused by the depletion of surface water flows resulting from pumping of water wells in the Arkansas River drainage, to which drainages of the Raton Basin are tributary. Because the waters of the Arkansas River are subject to control under the Arkansas River Compact, and waters in this basin are considered fully appropriated under most circumstances, the estimated stream depletion impacts require careful consideration. Under existing law, if the CBM water is put to beneficial use, offsets for stream depletion will be required where the aquifers are considered tributary. Results from this study suggest that all areas of CBM production in the Raton Basin of Colorado meet the criterion for tributary designation.

8.0 SUMMARY OF CONCLUSIONS

For this study, information was reviewed to provide background on the hydrogeologic setting related to CBM production in the Raton Basin; hydrogeologic, production and pressure data were analyzed to identify best-estimates of 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***: Over 500 billion cubic feet of gas have been produced in the Colorado portion of the Raton Basin since initiation of production in the 1980s. Based on data for the first half of 2006, present annual rates for gas production are estimated as 85 billion cubic feet per year and for water production are estimated at 16,000 acre-feet per year.

- ***Hydrogeologic setting***: The CBM wells produce from coals in the Raton and Vermejo Formations. Both formations are traversed by regional perennial streams where they outcrop. The Raton and Vermejo Formations both include sandstone, shale and siltstone, in addition to coal beds, and do not appear to contain regionally extensive, continuous, impermeable layers or aquitards.

- ***Estimation of aquifer parameters***: Aquifer parameters have been estimated separately for the Raton and Vermejo Formations in the Purgatoire watershed based on published test results and inferences drawn from formation thickness and other data. In the Cucharas watershed, little published data regarding aquifer parameters exists. In this area, one set of aquifer parameters were developed using data relating to both the combined Raton-Vermejo wells and Vermejo wells using limited production and pressure data.

- ***Stream depletion analysis***: The Glover method was applied in four distinct analyses to estimate stream depletion impacts: (a) to the Cucharas River from the combined Raton-Vermejo wells and the Vermejo wells; and, (b) to the Purgatoire River, using separately configured models for each of the Raton and Vermejo Formations. The projected stream depletions for all well locations exceed one tenth of one percent of the pumping rate in a period of 100 years. Total depletions in 2006 are estimated as approximately 2,500 acre-feet per year. The projections bear uncertainty as with any modeling analysis lacking data sufficient for thorough calibration. However, sensitivity analyses suggest that refinement of parameter estimates will not likely change the overall study conclusion.

- ***Suitability of the Glover method:*** Uncertainty exists in the projected depletions due to lack of sufficient data to fully characterize aquifer properties. Data regarding formation thickness and water production are excellent; however, absent data on fluid pressures at individual CBM production and observation wells, it is not possible to structure and parameterize a more detailed or complex model; nor is it possible to conclude that a more detailed or complex model would necessarily yield more accurate results. Alternate forms of the Glover solution that consider conditions such as partial penetration of a stream or semi-pervious streambed conditions are not recommended at this stage, due to the scale of this problem and the insensitivity of the solution to such conditions at the time/distances involved. Similarly, a three-dimensional finite difference model such as MODFLOW will not provide significant improvement in projections without additional data to populate the model. However, if fluid pressure and test data can be obtained from all CBM production wells, then, it is likely that an alternate model form may be justified and the accuracy of stream depletion estimates may be improved.

- ***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. Because streams in the Raton Basin are tributary to the Arkansas River, careful consideration of the stream depletions should be given with respect to the Arkansas River Compact.

9.0 REFERENCES

Abbot, A.L., A.L. Geldon, D. Cain, A.P.Hall, P.E. Edelmann, 1983. ***Hydrology of Area 61, Northern Great Plains and Rocky Mountain Coal Provinces, Colorado and New Mexico.*** The United States Geological Survey Water Resources Investigation OFR 83-132, 99 p.

Baltz, E.H., 1965. ***Stratigraphy and history of Raton Basin and notes on San Luis Basin, Colorado and New Mexico***. American Assoc. of Petroleum Geologists Bulletin, v.49, no.11, p.2041-2075.

Balleau, Peter, 2006. ***Hydrology of CBM development in Chicorica Watershed***. Technical Memorandum to File Raton/CBM, January 24, 2007, for the City of Raton.

Billingsley, L.T., 1978. ***Stratigraphy of the Pierre Shale, Trinidad Sandstone, and Vermejo Formation, Walsenburg area, Colorado – A deltaic model for sandstone and coal deposition.*** Proceedings of the Second Symposium on the Geology of Rocky Mountain Coal, 1977: Colorado Geological Survey Resource Series 4, p.23-34.

Carlton, D.R., 2006. ***Discovery and development of a giant coalbed methane resource, Raton Basin, Las Animas County, southeast Colorado***. The Mountain Geologist, v.43, no.3, p. 231-236.

Clarke, Paul, and P. Turner, 2002. ***Sedimentology and coalbed methane resources of the Raton Basin, USA***. Accessed March 12, 2007, at http://www.gees.bham.ac.uk/downloads/COALBED_%20METHANE.pdf

Clarke, P., C.T. Cornelius and P.Turner, 2004. ***A refined lithostratigraphy for the Raton Formation: Implications for alluvial heterogeneity, coal-forming environments, and coal bed distribution – Raton Basin***. AAPG Annual Convention abstracts, Denver.

Close, J.C., and R.R. Dutcher, 1990. ***Prediction of permeability trends and origins in coalbed methane reservoirs of the Raton Basin, New Mexico and Colorado in Bauer, P.W. and others, eds., Tectonic development of the southern Sangre de Cristo Mountains, New Mexico***. New Mexico Geological Society Guidebook, 41st Field Conference, p. 387-395.

COGCC, 2003. ***COGCC Raton Basin Baseline Study***. Accessed April 2007 at: (http://www.oil-gas.state.co.us/Library/RatonBasinReports.htm)

Cooper, J.R., 2005. ***Contrasting signatures of coal metamorphism due to dike and sill intrusions: an example from the Raton Basin, CO and NM***. In Geological Society of America Abstracts with Programs, Annual Meeting and Exposition, October.

Colorado Department of Water Resources, 2007. ***Well records***, accessed February 27 and 28, 2007, at: http://cdss.state.co.us/DNN/MapViewer/tabid/62/Default.aspx

Doherty, J., 2004. ***PEST – Model-independent parameter estimation user's manual.*** 5th ed. Watermark Numerical Computing, Brisbane, Australia.

Environmental Protection Agency, 2004. ***Evaluation of impacts to underground sources of drinking water by hydraulic fracturing of coalbed methane reservoirs.*** EPA 816-R-04-003.

ESN Rocky Mountain, 2003. ***Produced Gas and Water Testing of CBM Gas Wells in the Raton Basin, Huerfano and Las Animas Counties Colorado.*** Prepared for Colorado Oil and Gas Conservation Commission, 38 p.

Fenneman, N.M., 1931, ***Physiography of western United States***, New York, cl, 534 p.

Flores, R.M., and Bader, L.R., 1999, ***A summary of Tertiary coal resources of the Raton Basin, Colorado and New Mexico***, *in* U.S. Geological Survey Professional Paper 1625-A, Chapter SR.

Freeze, R.A and J.A. Cherry, 1979. ***Groundwater***. Prentice-Hall, Inc.

Geldon, A.L., P.O. Abbott, 1985. ***Selected Climatological and Hydrologic Data, Raton Basin, Huerfano and Las Animas Counties, Colorado and Colfax County, New Mexico***. U.S. Geological Survey Open-File Report 84-138, 273p.

Geldon, A.L., 1989, ***Ground-water hydrology of the central Raton Basin, Colorado and New Mexico.*** U.S. Geological Survey Water-Supply Paper 2288, 81p.

Glover, R.E., and G.G. Balmer, 1954. ***River depletion resulting from pumping a well near a river.*** Trans. Am. Geophysical Union, v. 35, pp. 468-470.

Hantush, M.S., 1955. ***Discussion of "River depletion resulting from pumping a well near a river".*** Trans. Am. Geophysical Union, v. 36, pp. 2829-2838

Hantush, M.S., 1965. ***Wells near Streams with Semipervious Beds.*** Journal of Geophysical Research, v. 70, no. 12, pp. 345-347

Hemborg, T.H., 1998. ***Spanish Peak Field, Las Animas County, Colorado: Geologic setting and early development of a coalbed methane reservoir in the central Raton Basin***. Colorado Geological Survey, Resource Series 33, 34p.

Higley, D.K., T.A. Cook, R.M. Pollastro, R.R. Charpentier, T.R. Klett, and C.J. Schenk, 2007. ***Executive Summary – 2005 Assessment of Undiscovered Oil and Gas Resources in the Raton Basin-Sierra Grande Uplift Province of Colorado and New Mexico***, in Higley, D.K., compiler, ***Petroleum systems and assessment of undiscovered oil and gas in the Raton Basin-Sierra Grande Uplift Province, Colorado and New Mexico*** – USGS Province 41: U.S. Geological survey Digital Data Series DDS-69-N, ch. 1, 2p.

Howard, W.B. 1982. ***The hydrogeology of the Raton Basin, South-Central Colorado.*** M.A. Thesis, Department of Geology, Indiana University.

Jenkins, C.T., 1968. ***Computation of rate and volume of stream depletion by wells***. Chapter D-1, Techniques of Water-Resource Investigations of the United States Geological Survey. Book 4 of USGS Hydrologic Analysis and Interpretation.

Johnson, R.B., 1969. ***Geologic map of the Trinidad Quadrangle, south-central Colorado:*** U.S. Geological Survey Miscellaneous Geological Investigation Map I-558.

Johnson, R.B., 1961, ***Patterns and origin of radial dike swarms associated with West Spanish Peak and Dike Mountain, South-Central Colorado***: Geological Society of America Bulletin, v. 72, p.579-590.

Lee, W.T., 1917. ***Geology of the Raton Mesa and other regions in Colorado and New Mexico, in Lee, W.T., and Knowlton, F.H., eds., Geology and Paleontology of Raton Mesa and other regions in Colorado and New Mexico.*** U.S. Geological Survey Professional Paper 101, 450p.

Lohman, S.W., 1972. ***Ground-water hydraulics***. U.S. Geological Survey Professional Paper 708.

Manzolillo, C.D., 1976, ***Stratigraphy and depositional environments of the Upper Cretaceous Trinidad Sandstone, Trinidad-Aquilar area, Las Animas County, Colorado***. Colorado School of Mines M.S. Thesis T-1847, 147p.

Martin and Wood Water Consultants, Inc., 1996. ***Final groundwater assessment report for Basin Property Resources, Inc. Property.***

Mavor, M.J., J.C. Close, and T.J. Pratt, 1991. ***Western Cretaceous coal seam project; summary of the completion optimization and assessment laboratory (COAL) site***. Gas Research Institute, GRI-91-0377.

McWhorter, D. and D.K. Sunada, 1981. ***Ground-water Hydrology and Hydraulics***. Water Resources Publications, Littleton, Colorado.

Orth, C.J., J.S. Gilmore, J.D. Knight, C.L. Pillmore, R.H. Tschudy, J.E. Fassett, 1981. ***An Iridium abundance anomaly at the palynological Cretaceous-Tertiary boundary in northern New Mexico***. Science, v.214, p.1341-1343.

Petroglyph Operating Company, 2007. ***Water Production and Pressure Data from Select Wells*** Electronic data obtained from Tom Melland, Petroglyph Operating Company, Inc.

Pillmore, C.L. and R.M. Flores, 1984, ***Field guide and discussions of coal deposits, depositional environments, and the Cretaceous-Tertiary boundary, southern Raton Basin,*** *in* Lintz, J., Jr., ed***., Western Geological Excursions***: Geological Society of America, Annual Meeting Guidebook, V.3, p.1-51.

-, 1987, ***Stratigraphy and depositional environments of the Cretaceous-Tertiary boundary clay and associated rocks, Raton Basin, New Mexico and Colorado***; *in* Fassett, J. and Rigby, J. eds., ***The Cretaceous-Tertiary boundary in the San Juan and Raton Basins, New Mexico and Colorado***: The Geological Society of America, Special Paper 209, p.111-130.

Rice, D.D., and T.M. Finn, 1996, ***Coal-bed gas plays, Raton Basin-Sierra Grande Uplift province, in Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 national assessment of U.S. oil and gas resources-results, methodology, and supporting data***. U.S. Geological Survey Digital Data Series DDS-30, Release 2.

Robinson-Roberts, L.N., and J. Uptgrove, 1991. ***USGS Coal Investigations Map C-138***.

Seacrest Group, 2003. ***Water Quality Data Collected from Water Wells in the Raton Basin, Colorado.*** Prepared for Colorado Oil and Gas Conservation Commission, 42 p.

Stevens, S.H., T.E. Lombardi, B.S. Kelso, and J.M. Coates, 1992. ***A geologic assessment of natural gas from coal seams in the Raton and Vermejo Formations, Raton Basin: Advanced Resource International, Inc.***, topical report prepared for the Gas Resource institute under contract no. 5091-214-2316, GRI 92/0345, 84p.

S.S. Papadopulos & Associates, Inc., 2006. ***Coalbed methane stream depletion assessment study, San Juan Basin, Colorado.***

Theis, C.V., 1935. ***The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage***. Trans. Am. Geophysical Union, v. 16, p. 519-524.

Topper, Ralf, K.L. Spray, W.H. Bellis, J.L. Hamilton, and P.E. Barkmann, 2003. ***Ground water atlas of Colorado***. Colorado Geological Survey Special Publication 53.

Tremain, C.M., 1980. ***The coal bed methane potential of the Raton Mesa Coal region, Raton Basin, Colorado***. Colorado Geological Survey Open-File Report 80-4, 48p.

Tschudy, R.H., C.L. Pillmore, C.J. Orth, J.S.Gilmore and J.D. Knight, 1984. ***Disruptions of the terrestrial plant ecosystem at the Cretaceous-Tertiary boundary***. Western Interior: Science, v. 225, no. 4666, p.1030-1034.

Tyler, R., W.A. Ambrose, A.R. Scott and W.R. Kaiser, 1991, ***Coalbed methane potential of the greater Green River, Piceance, Powder River, and Raton Basins***. Univ. of Texas at Austin, Bureau of Economic Geology, topical report prepared for the Gas Research Institute under contract no. 5091-214-2261, GRI-95/0320, 219p.

Tyler, R., W.R. Kaiser, A.R. Scott, et al, 1995. ***Geologic and hydrologic assessment of natural gas from coal: Greater Green River, Piceance, Powder River, and Raton Basins, Western United States.*** Austin, Texas Bureau of Economic Geology, Report of Investigations 228.

U.S. Geological Survey, 2005. **Assessment of Undiscovered Oil and Gas Resources of the Raton Basin–Sierra Grande Uplift Province of New Mexico and Colorado, 2004.** Fact Sheet 2005–3027, 2p.

Watts, K.R., 2006a. ***Hydrostratigraphic Framework of the Raton, Vermejo and Trinidad Aquifers of the Raton Basin, Las Animas County, Colorado***. United States Geological Survey Scientific Investigations Report 2006-5129, 31 p.

Watts, K.R., 2006b. ***A Preliminary Evaluation of Vertical Separation between Production Intervals of Coalbed-Methane Wells and Water-Supply Wells in the Raton Basin, Huerfano and Las Animas Counties, Colorado, 1999-2004***. United States Geological Survey Scientific Investigations Report 2006-5109, 9 p.

Wolfe, D. and G. Graham, 2002. ***Water rights and beneficial use of coal bed methane produced water in Colorado***. Department of Natural Resources, Colorado Division of Water Resources.

Wood, G.H., Fr., R.B. Johnson, and G.H. Dixon, 1956. ***Geology and coal resources of the Gulnare, Cucharas Pass, and Stonewall area, Huerfano and Las Animas counties, Colorado***: U.S. Geological Survey Coal Investigations Map C-26, scale 1:31,680, 2 sheets.

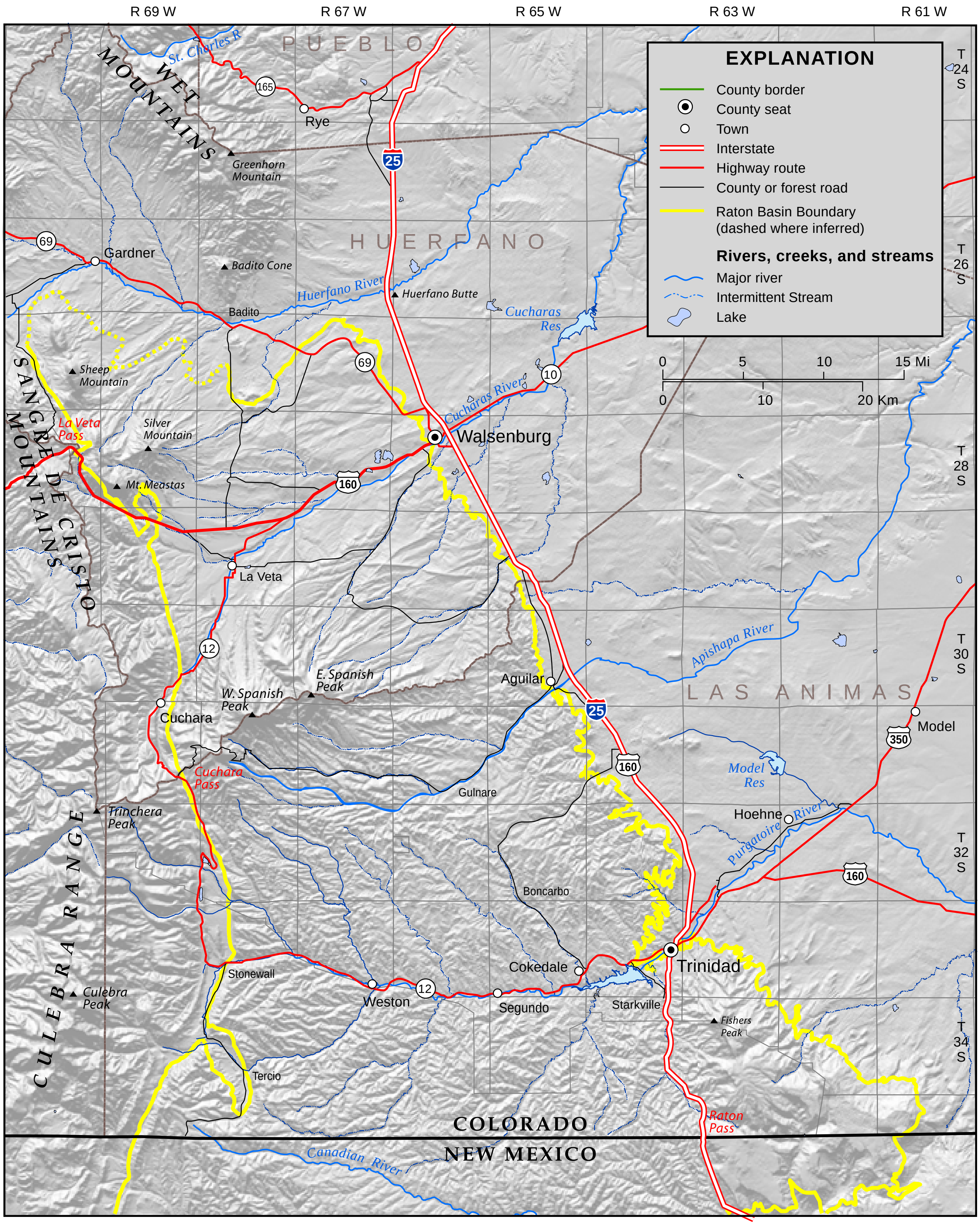


Figure 1.1 Geographic Reference Map for the Raton Basin and its Major Drainage Systems

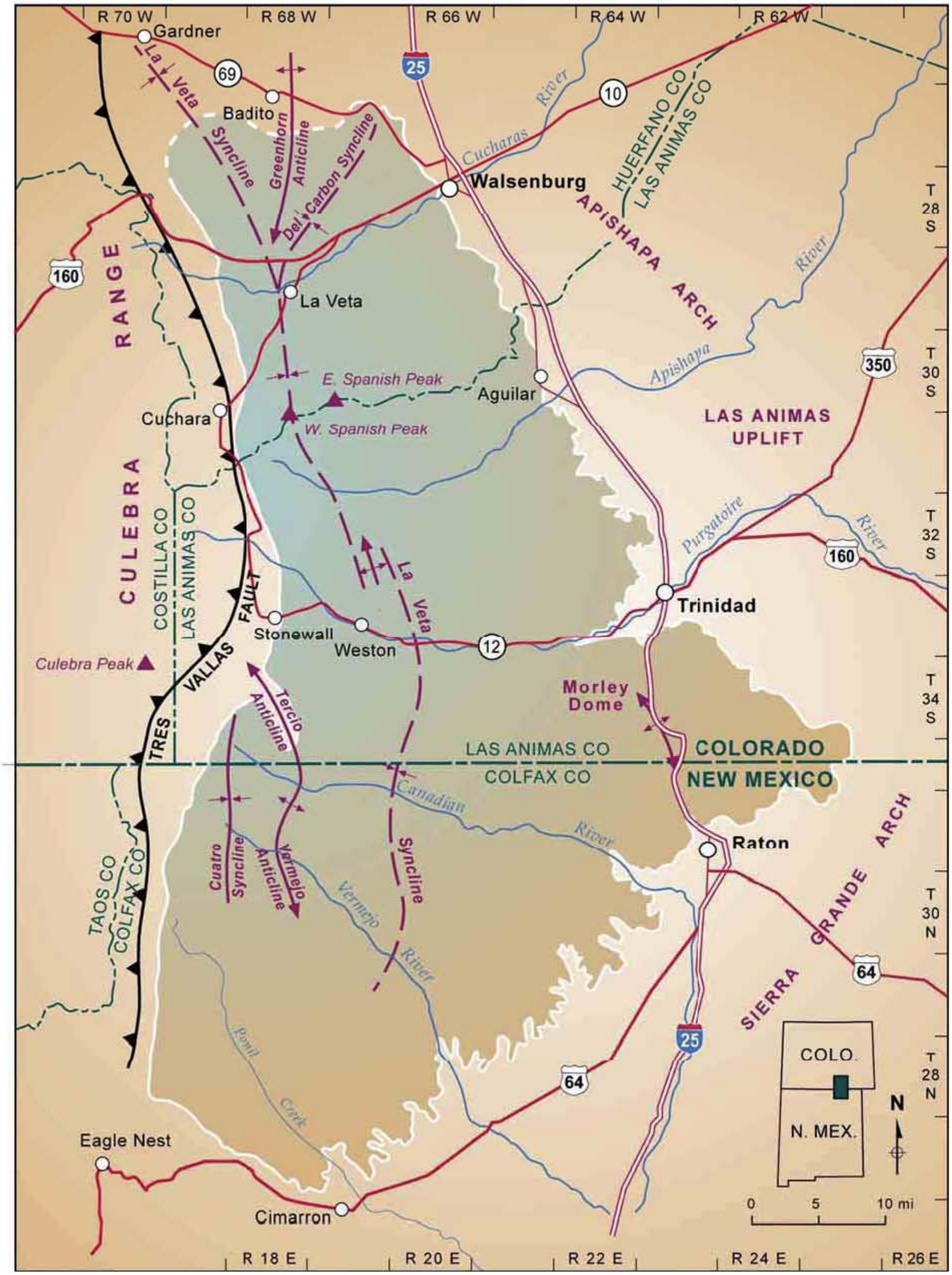


Figure 3.1 Location of the Raton Basin in Colorado and New Mexico Showing Structural Features

ERA	PERIOD / EPOCH		FORMATION	THICKNESS (FT)	LITHOLOGY
CENOZOIC	Recent			0—30	Alluvium, basalt flows
	Miocene		Devils Hole Formation	25–1,300	Light-gray conglomeratic tuff and conglomerate
	Oligocene		Farisita Formation	0–1,200	Buff conglomerate and sandstone
	Eocene		Huerfano Formation	0–2,000	Variegated maroon shale and red, gray, and tan claystone
			Cuchara Formation	0–5,000	Red, pink, and white sandstone, and red, gray, and tan claystone
	Paleocene		Poison Canyon Formation	0–2,500	Buff arkosic conglomerate and sandstone, yellow siltstone, and shale
			Raton Formation	0–2,000	Light-gray to buff sandstone, dark-gray siltstone, shale, and coal; conglomerate at base
MESOZOIC	Upper Cretaceous		Vermejo Formation	0–380	Dark-gray silty and coaly shale, buff to gray carbonaceous siltstone, and sandstone beds; coal
			Trinidad Sandstone	0–260	Light-gray to buff sandstone
			Pierre Shale	1,300–2,300	Dark-gray fissile shale and siltstone
		Niobrara Group	Smokey Hill Marl	560–850	Yellow chalk, marine gray shale and thin white limestone; and light-gray limestone at base
			Fort Hayes Limestone	0–55	
		Benton Group	Codell Sandstone	0–30	Brownish sandstone, dark-gray shale, gray limestone and gray shale
			Carlile Shale	165–225	
			Greenhorn Limestone	30–80	
			Graneros Shale	185–400	
	Lower Cretaceous		Dakota Sandstone	100–200	Buff sandstone, buff conglomerate sandstone, and dark-gray shale
			Purgatoire Formation	100–150	
	Jurassic		Morrison Formation	150–400	Variegated maroon shale, gray limestone, red siltstone, gypsum, and gray sandstone
			Ralston Creek Formation	30–100	
			Entrada Sandstone	40–100	
	Triassic		Dockum Group	0–1,200	Red sandstone, calcareous shales, and thin limestones
PALEOZOIC UNDIVIDED				5,000–10,000	Variegated shales, arkose, conglomerates, and thin marine limestone

(After Tremain, 1980)

Figure 3.2 Stratigraphic Sequence of the Mesozoic and Younger Aged Geologic Units in the Raton Basin

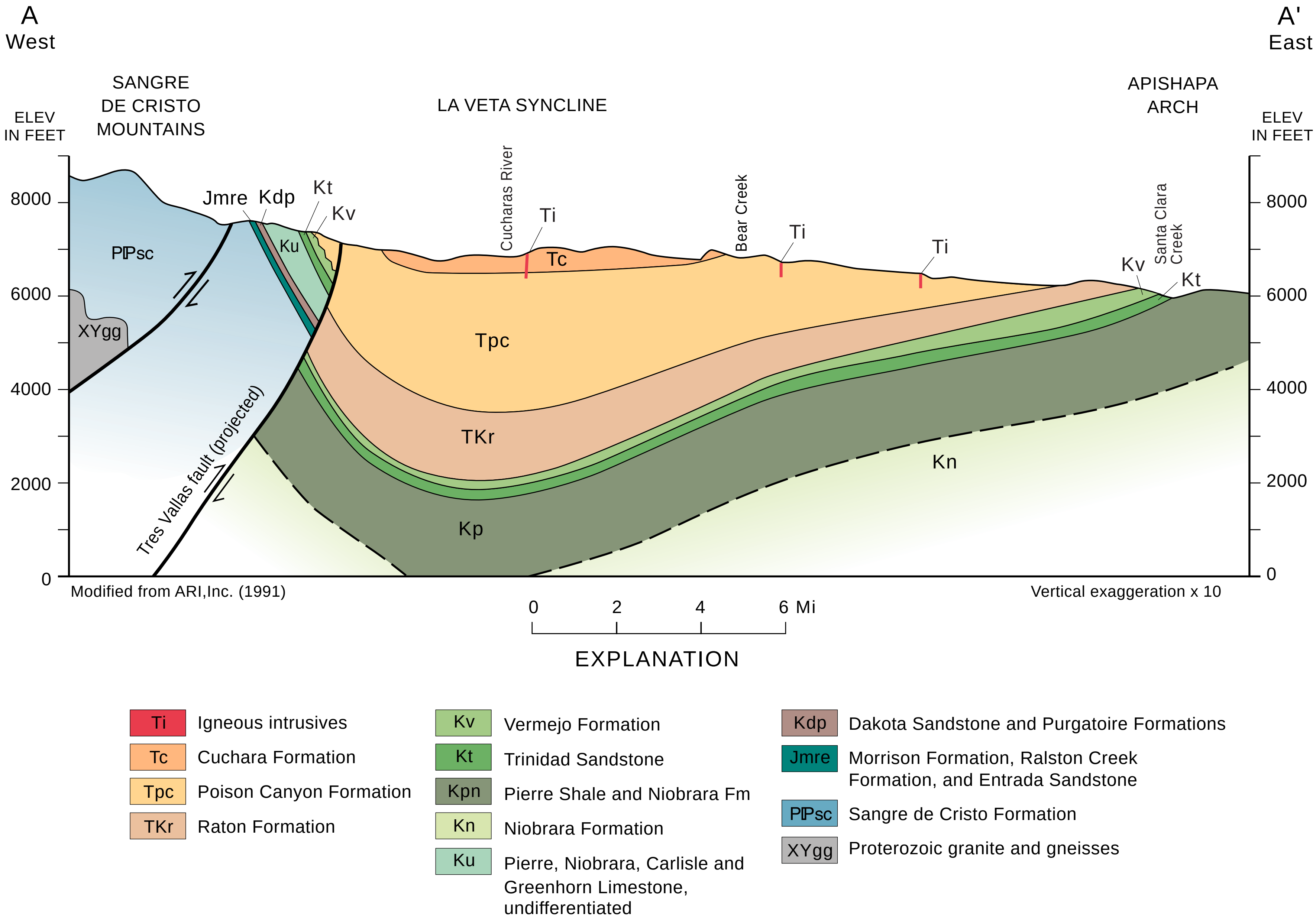


Figure 3.3 West to East Geologic Cross Section in the Northern Portion of the Basin near the Huerfano/Las Animas County Line

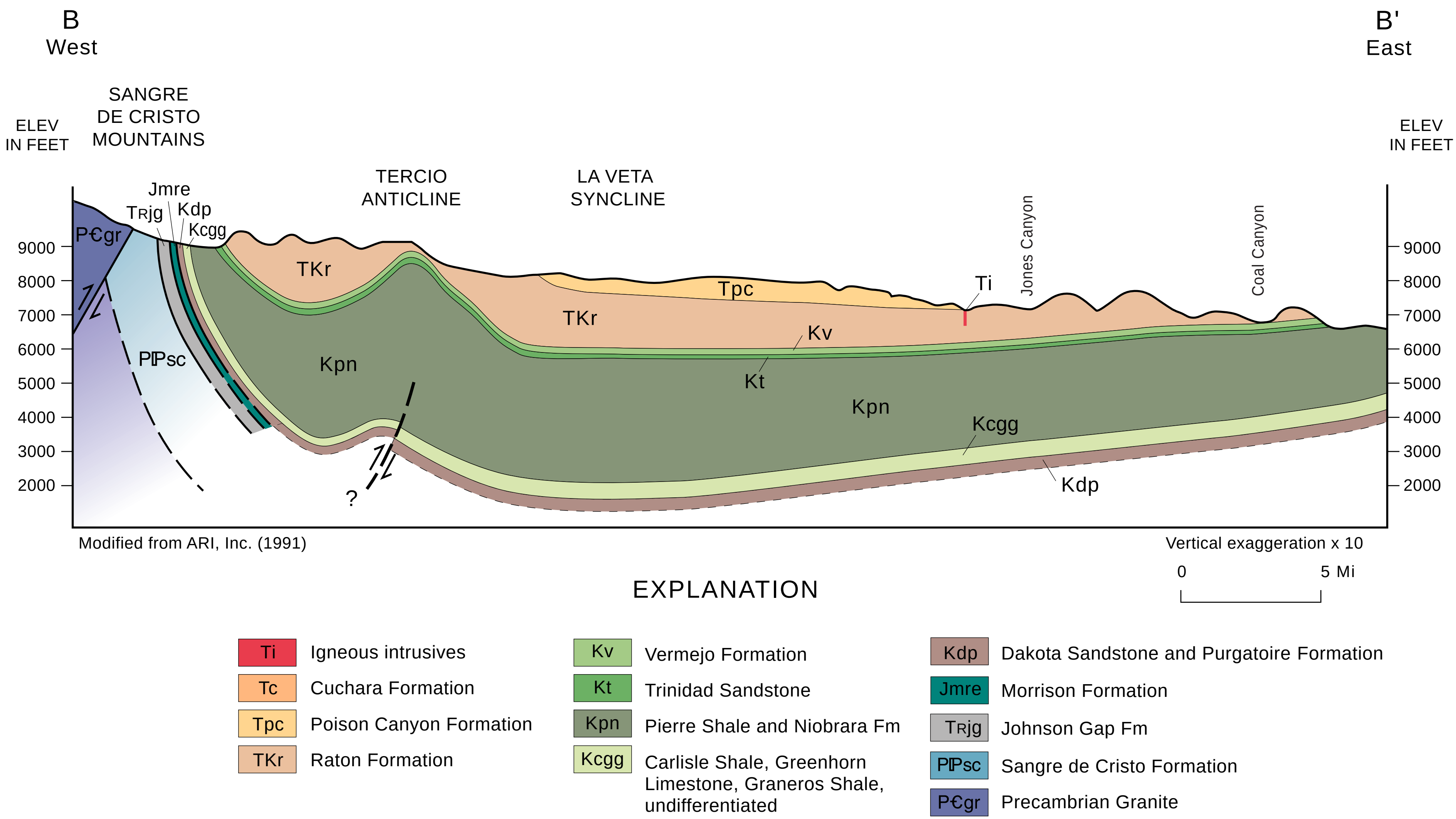


Figure 3.4 West to East Geologic Cross Section in the Southern Portion of the Basin near the Colorado/New Mexico State Line

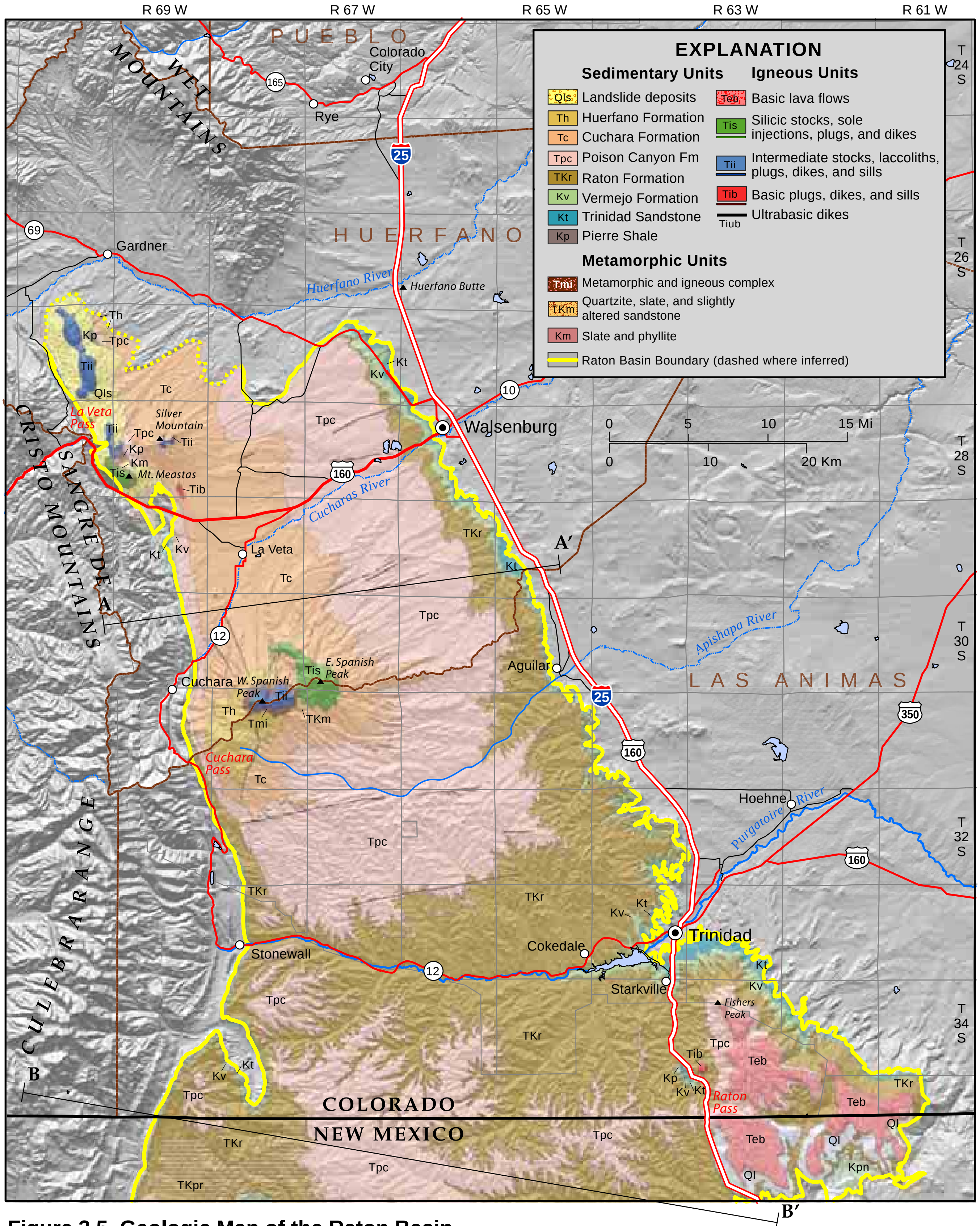
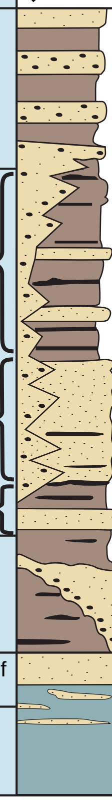


Figure 3.5 Geologic Map of the Raton Basin

AGE		FORMATION NAME	GENERAL DESCRIPTION	LITHOLOGY	APPROX. THICKNESS IN FEET
TERTIARY	PALEOCENE	POISON CANYON FORMATION	SANDSTONE–Coarse to conglomeratic beds 13–50 feet thick. Interbeds of soft, yellow-weathering clayey sandstone. Thickens to the west at expense of underlying Raton Formation		0–2,500
TERTIARY / MESOZOIC	PALEOCENE / UPPER CRETACEOUS	RATON FORMATION	Formation intertongues with Poison Canyon Formation to the west UPPER COAL ZONE–Very fine grained sandstone, siltstone, and mudstone with carbonaceous shale and thick coal beds BARREN SERIES–Mostly very fine to fine grained sandstone with minor mudstone, siltstone, with carbonaceous shale and thin coal beds LOWER COAL ZONE–Same as upper coal zone; coal beds mostly thin and discontinuous. Conglomeratic sandstone at base; locally absent		*600–1,100* 0–2,000 *180–600* ←K/T Boundary *150–300*
MESOZOIC	UPPER CRETACEOUS	VERMEJO FORMATION	SANDSTONE–Fine to medium grained with mudstone, carbonaceous shale, and extensive, thick coal beds. Local sills		0–380
MESOZOIC	UPPER CRETACEOUS	TRINIDAD SANDSTONE	SANDSTONE--Fine to medium grained; contains casts of *Ophiomorpha*		0–260
MESOZOIC	UPPER CRETACEOUS	PIERRE SHALE	SHALE--Silty in upper 300 ft. Grades up to fine grained sandstone. Contains limestone concretions		1,300-2,300

Adapted from Flores and Bader (1999), Tyler and others (1991), and Tremain (1980).

Figure 3.6 Detailed Stratigraphic Chart of the Upper Cretaceous and Younger Units in the Raton Basin

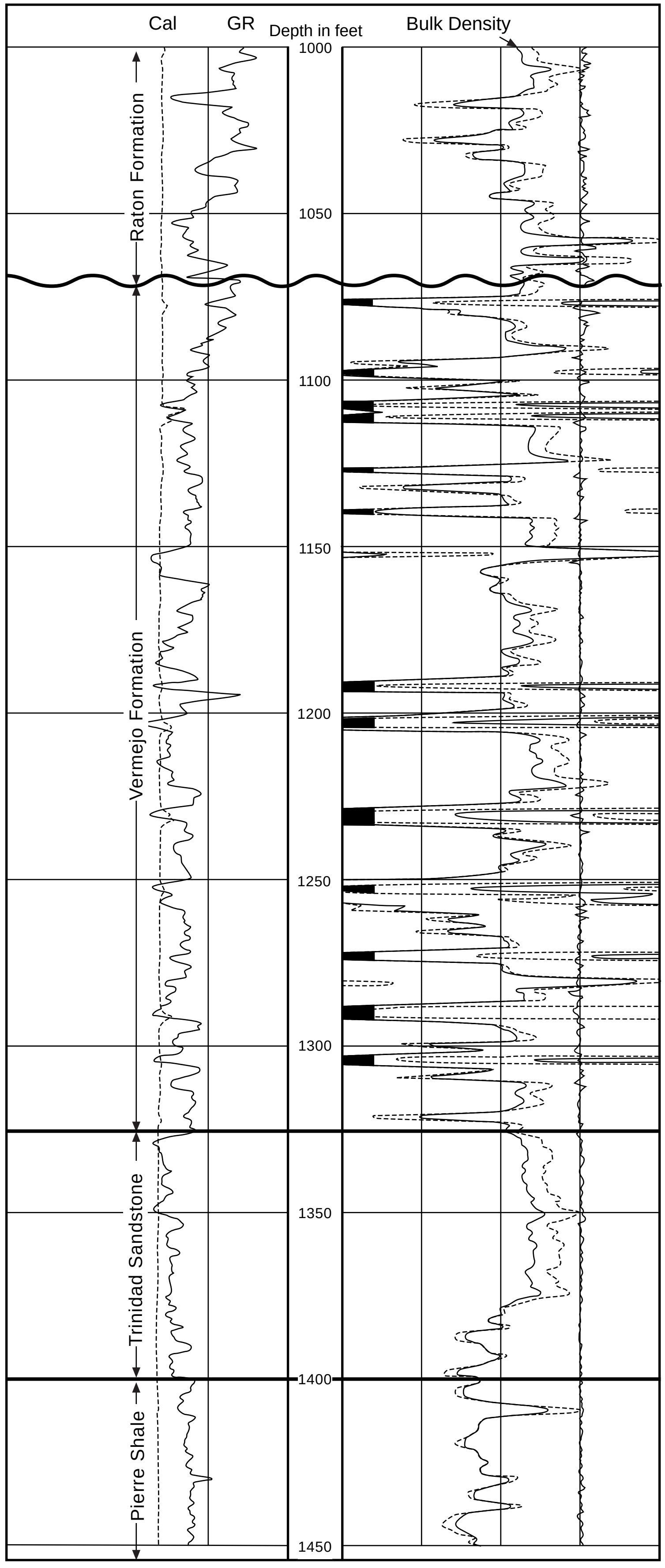


Figure 3.7 Geophysical Log Response of the Upper Cretaceous Formations in the Spanish Peak Field

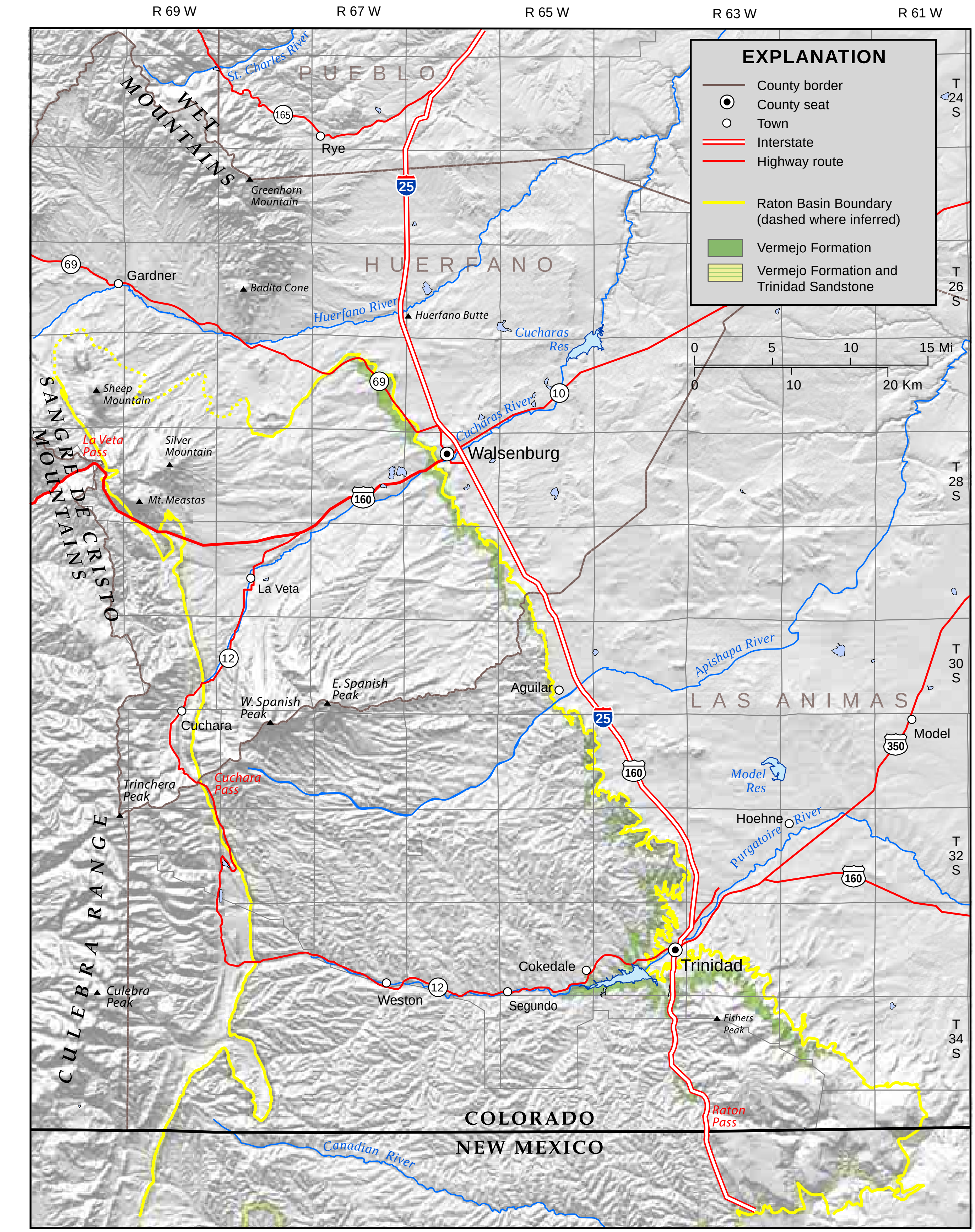


Figure 3.8 Outcrop Map of the Vermejo Formation

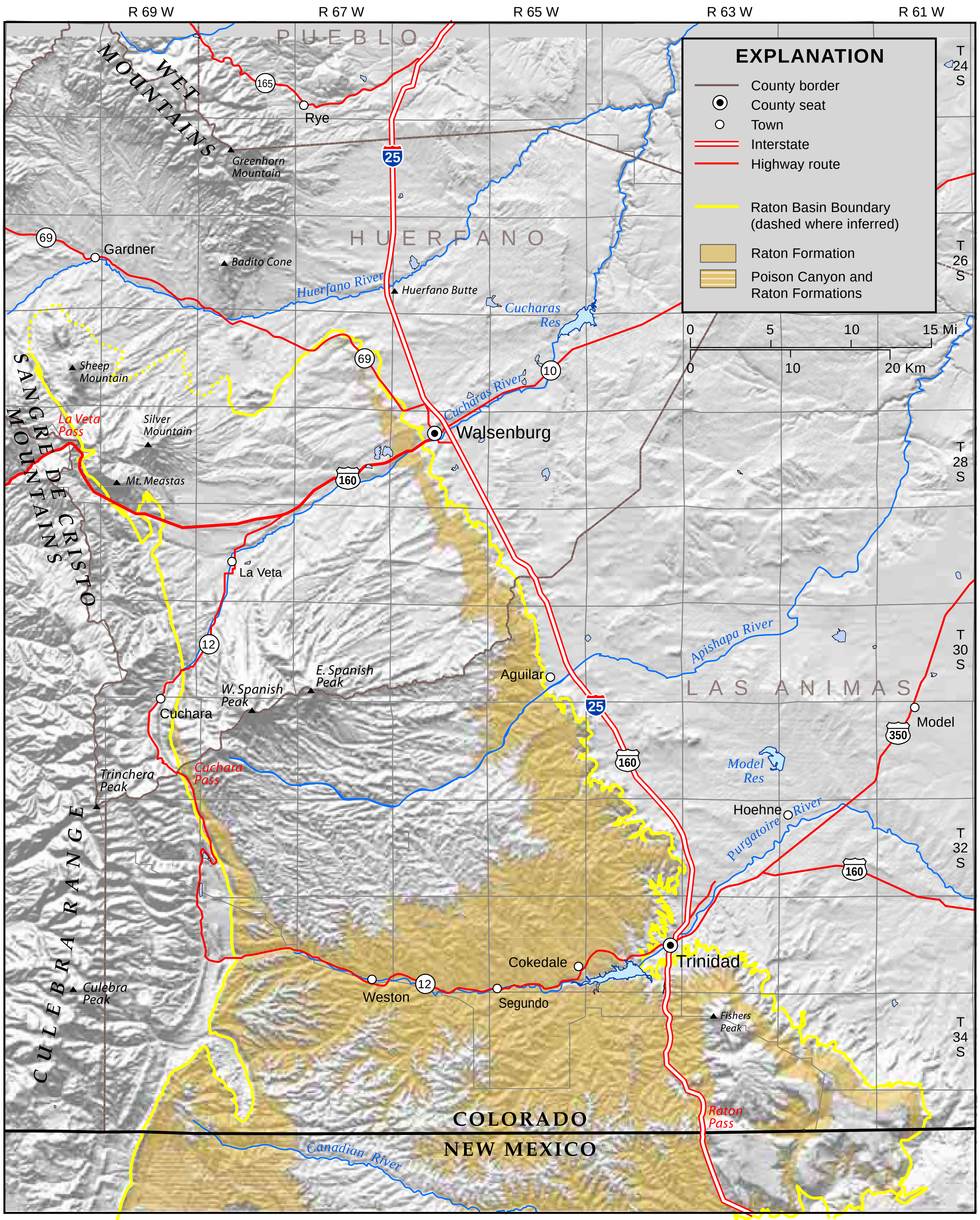


Figure 3.9 Outcrop Map of the Raton Formation

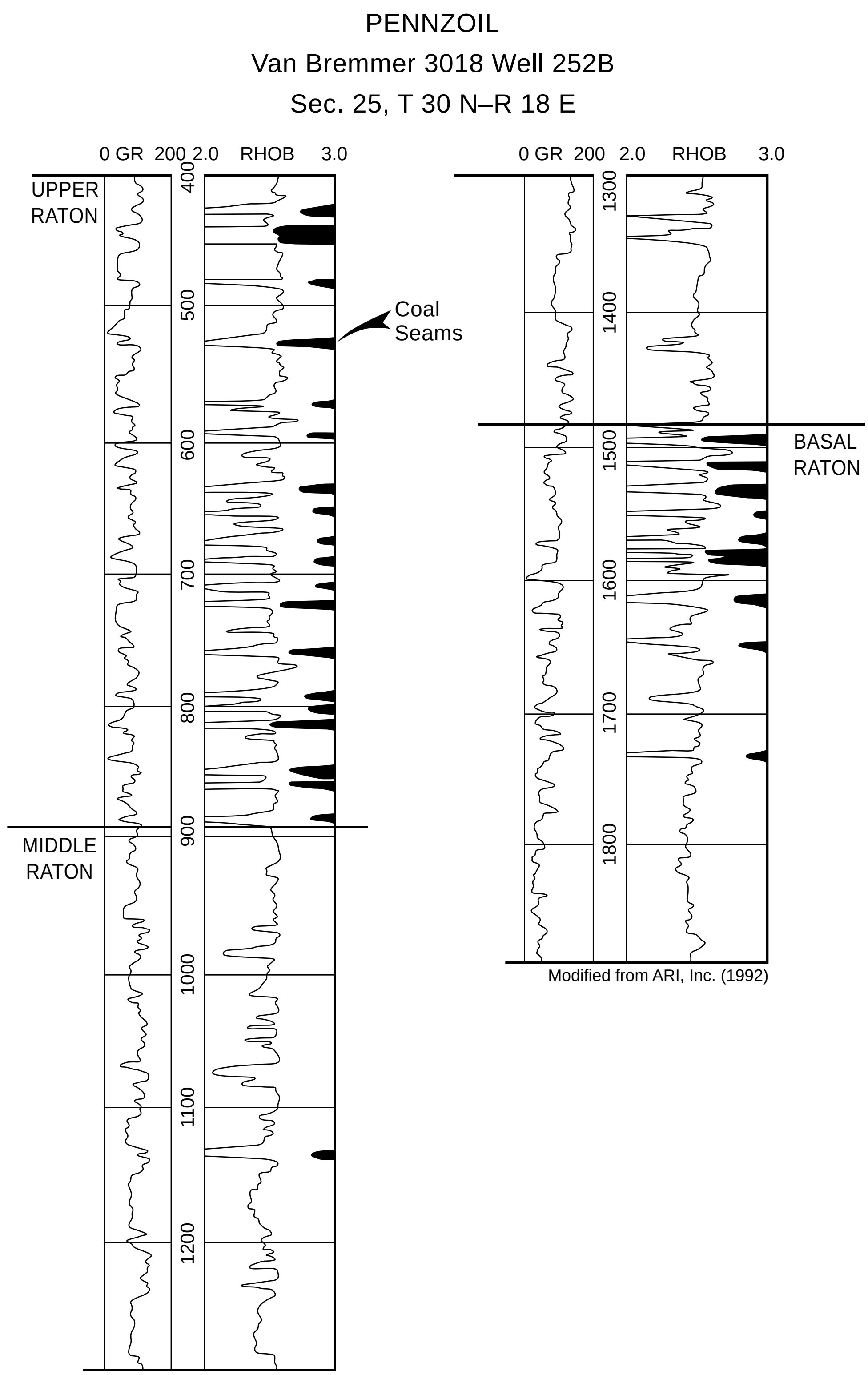


Figure 3.10 Geophysical Log Response of the Raton Formation near Casa Grande, New Mexico

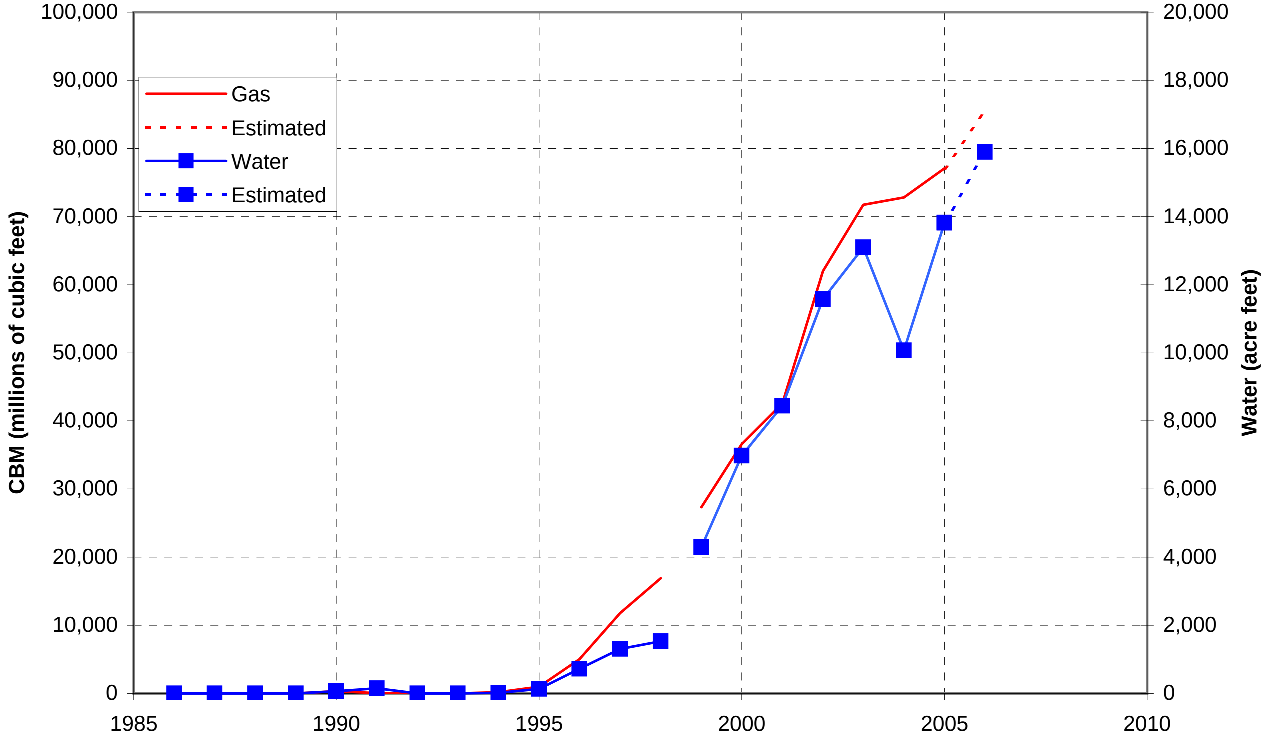
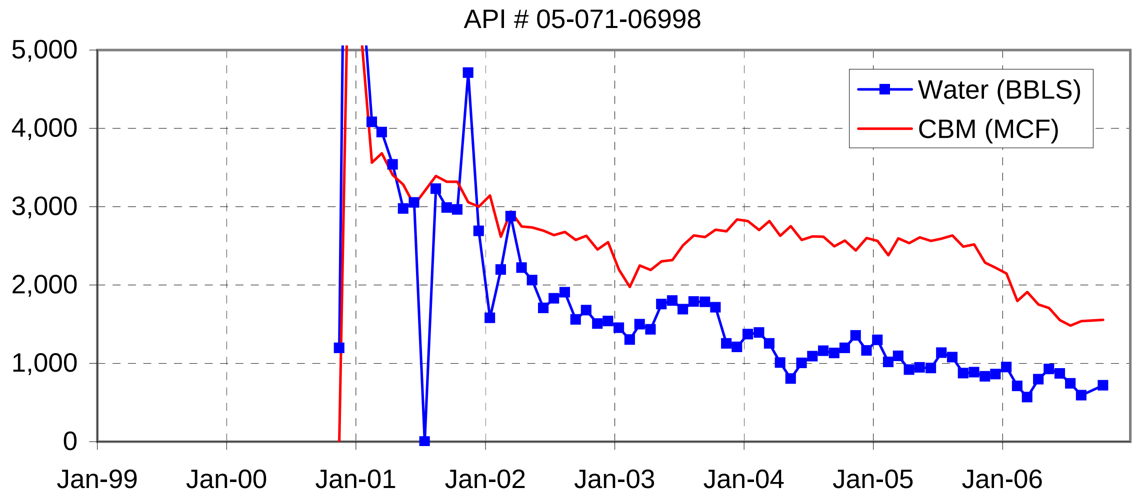
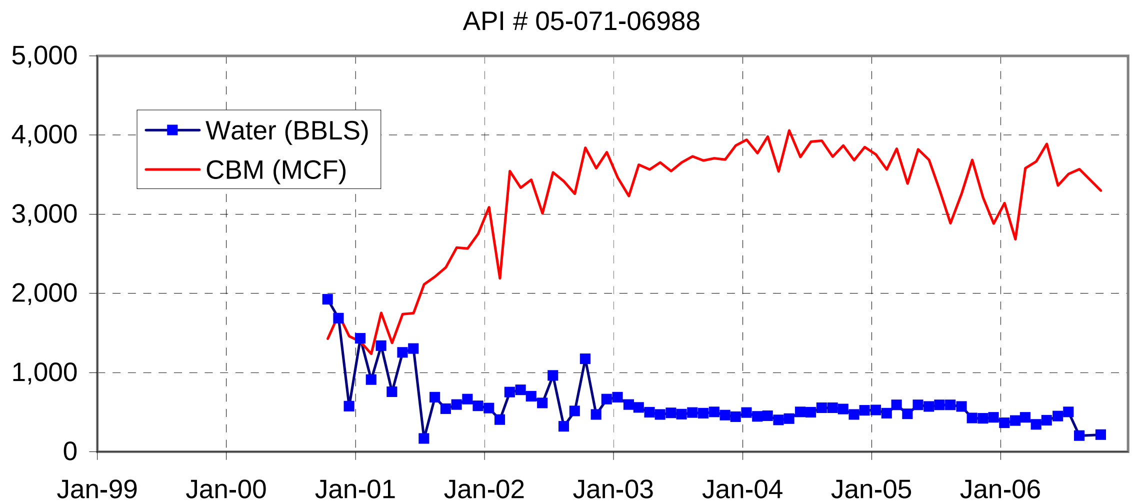


Figure 4.1 Raton Basin Annual CBM Gas and Water Production





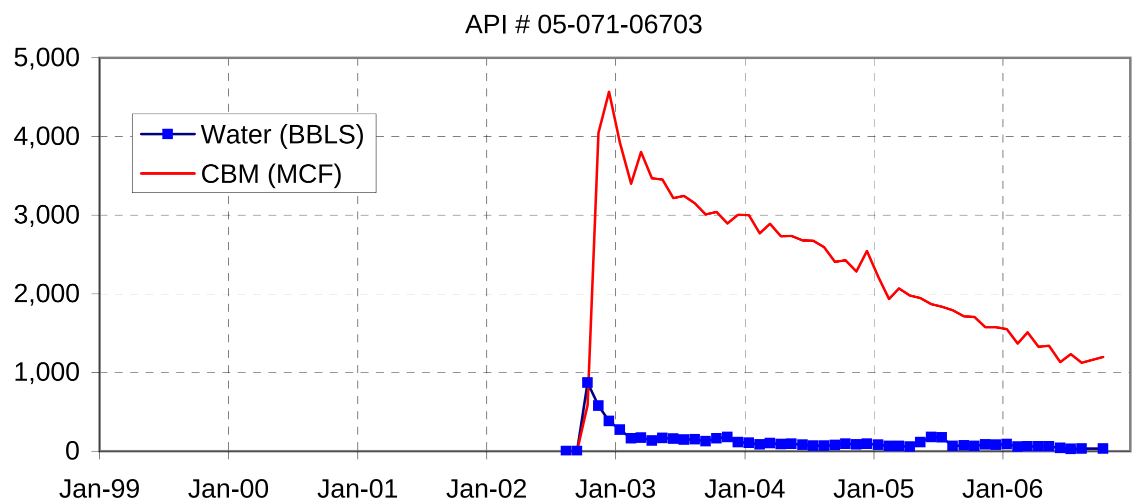


Figure 4.2 Vermejo Formation CBM Gas and Water Production

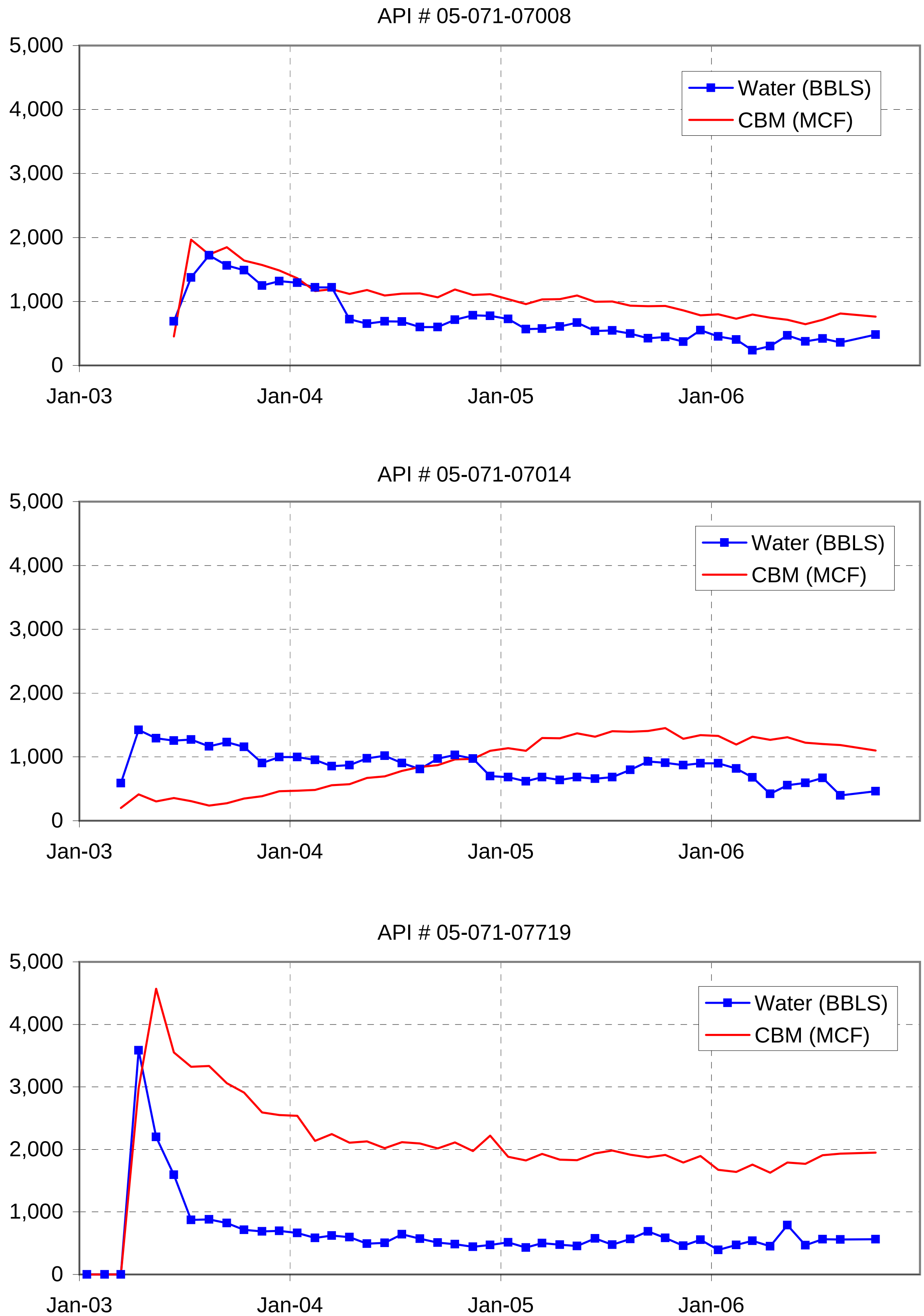


Figure 4.3 Raton Formation CBM Gas and Water Production

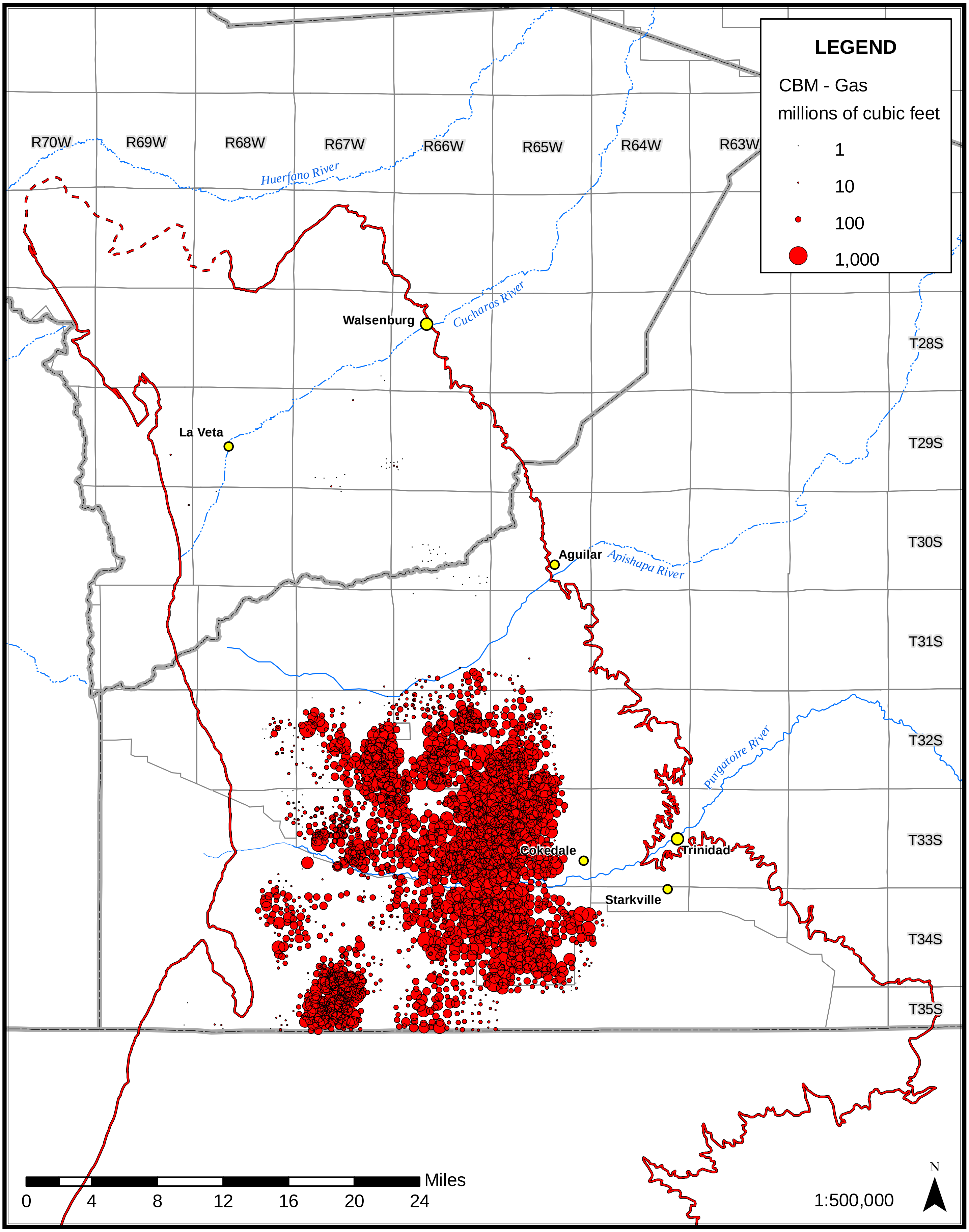


Figure 4.4 Cumulative Gas Production in the Raton Basin

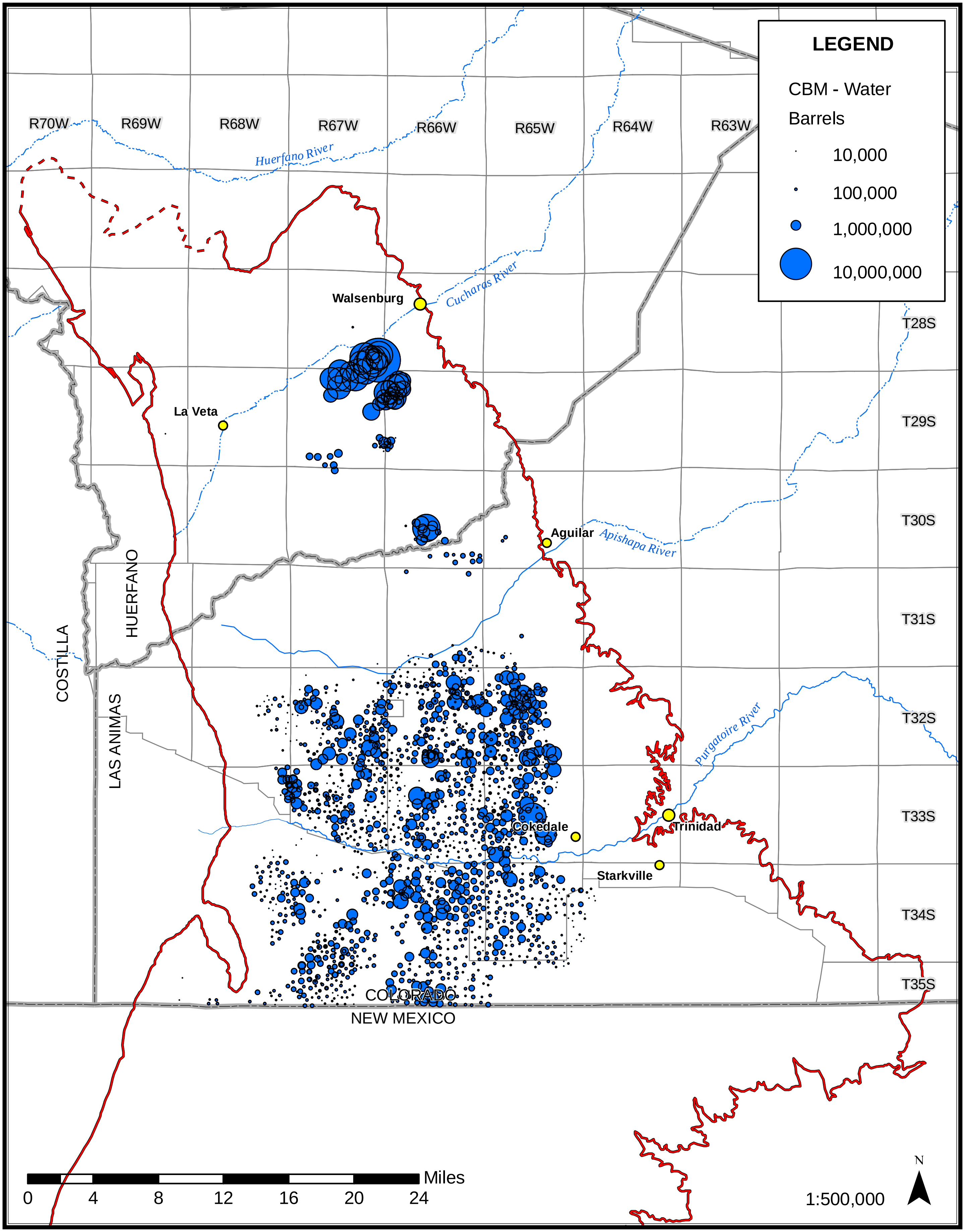


Figure 4.5 Cumulative Water Production in the Raton Basin

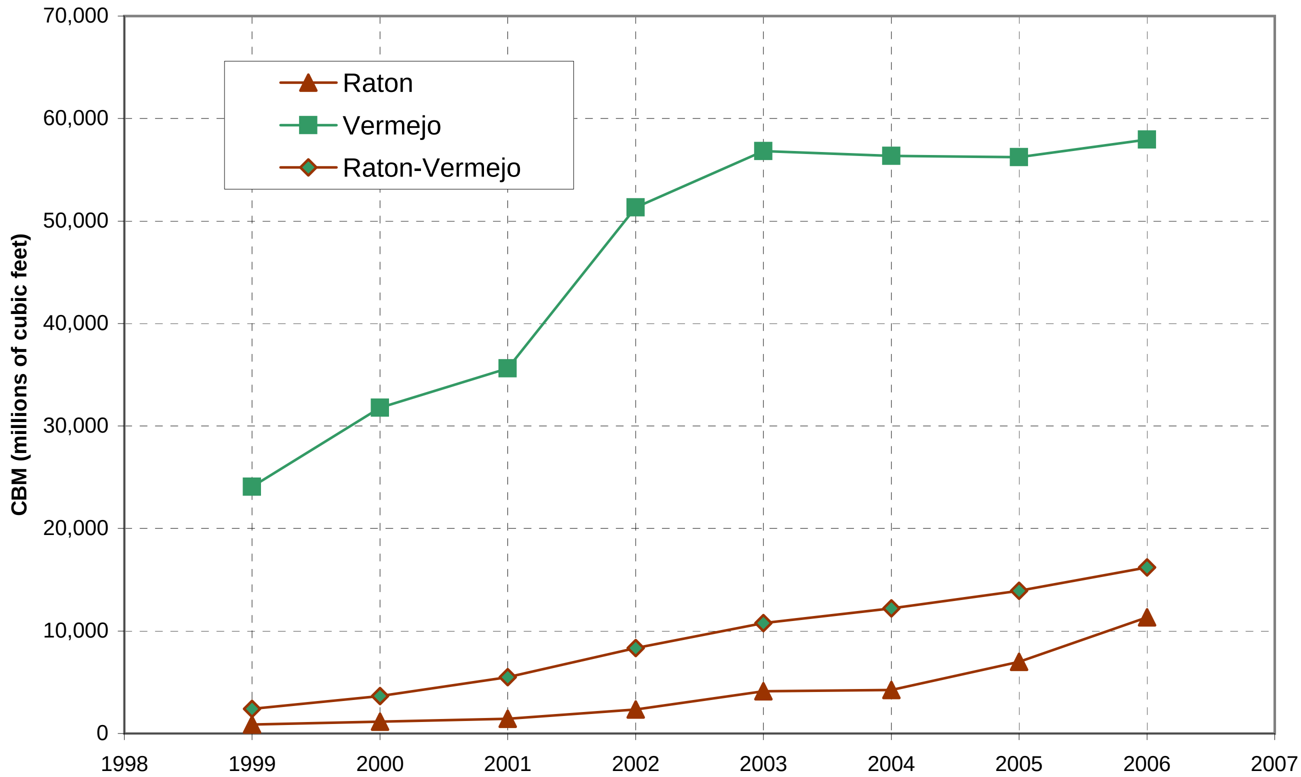


Figure 4.6 Annual Gas Production for Raton, Vermejo and Commingled Raton-Vermejo Wells, 1999 to 2006

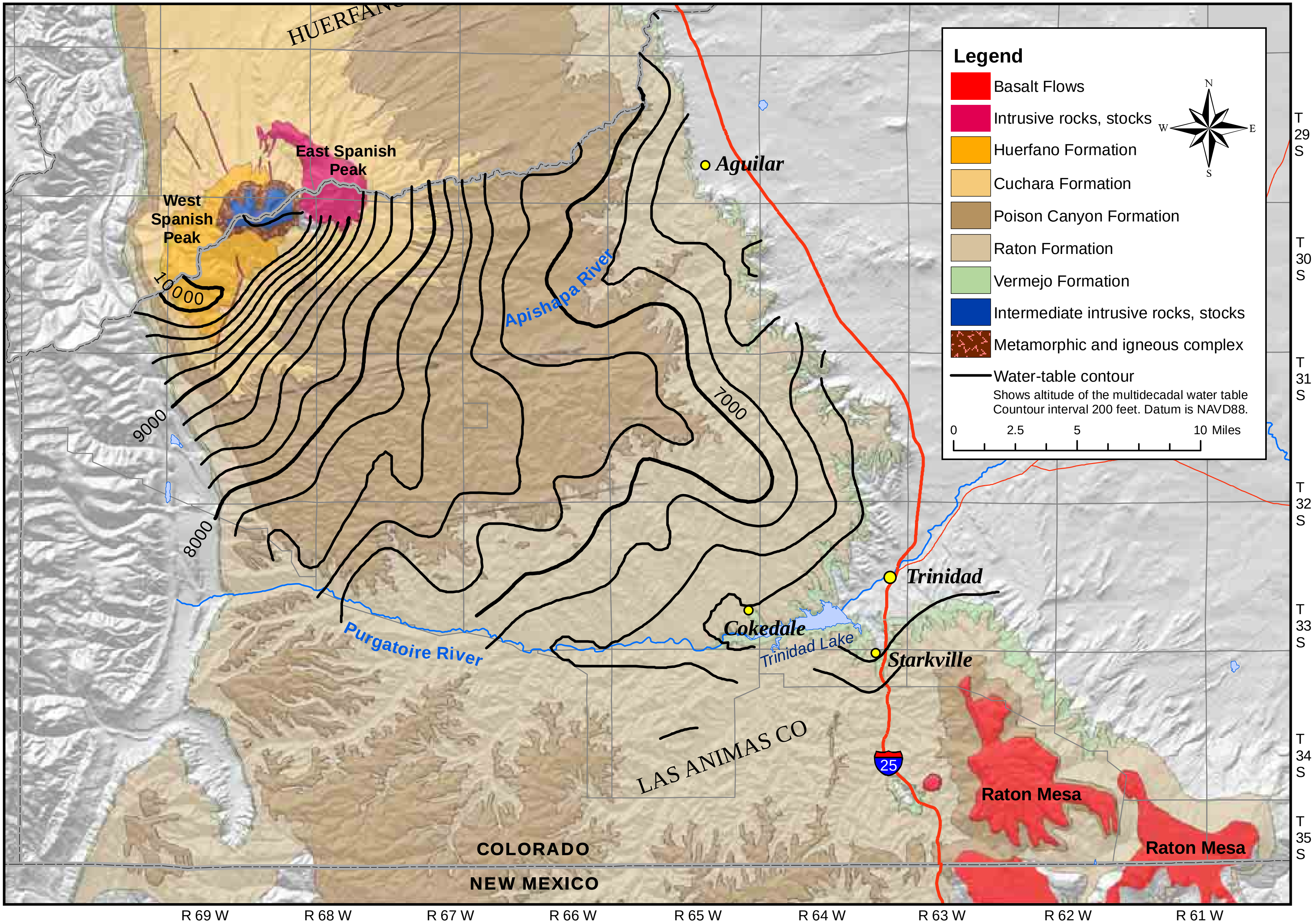
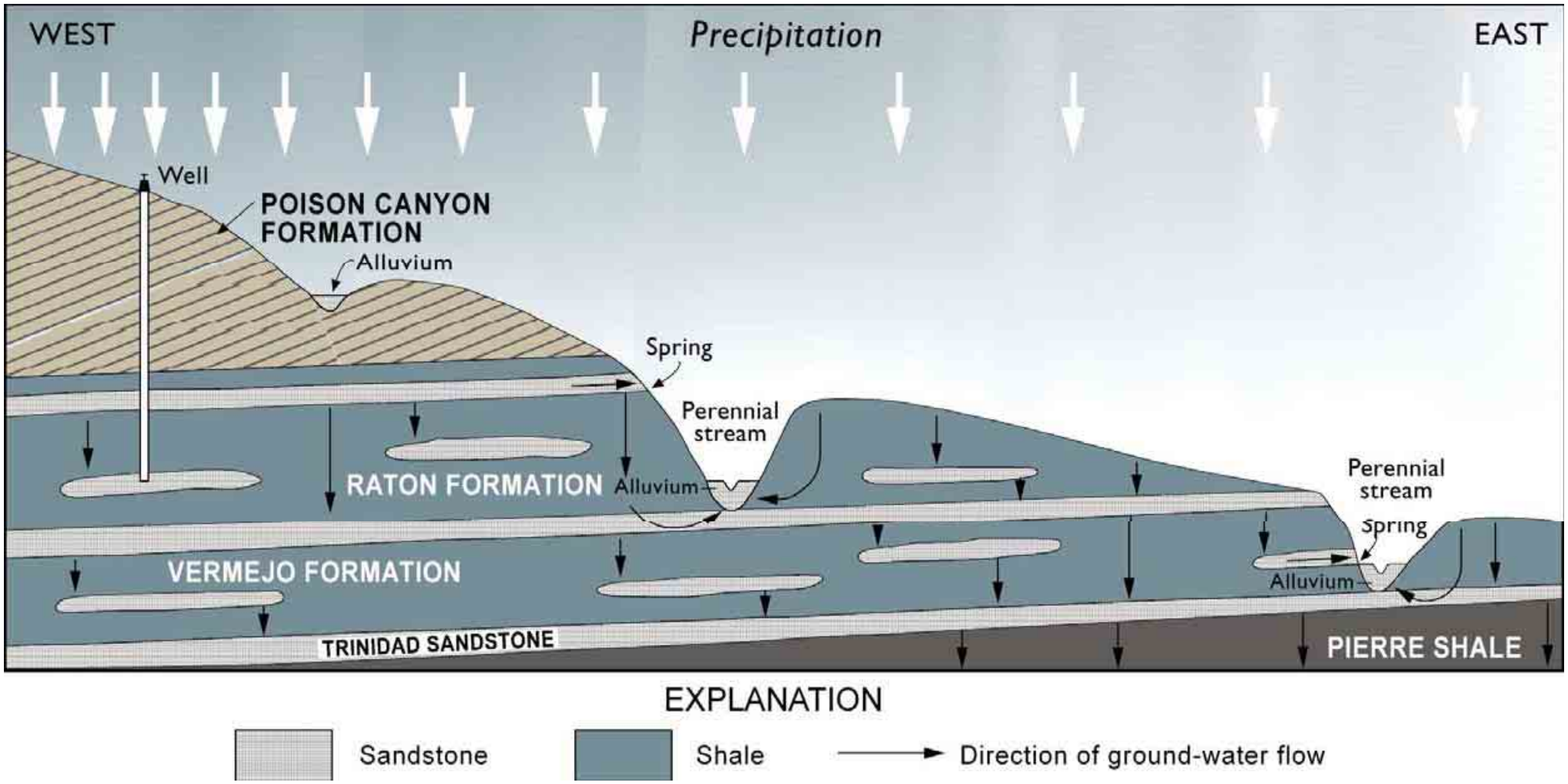
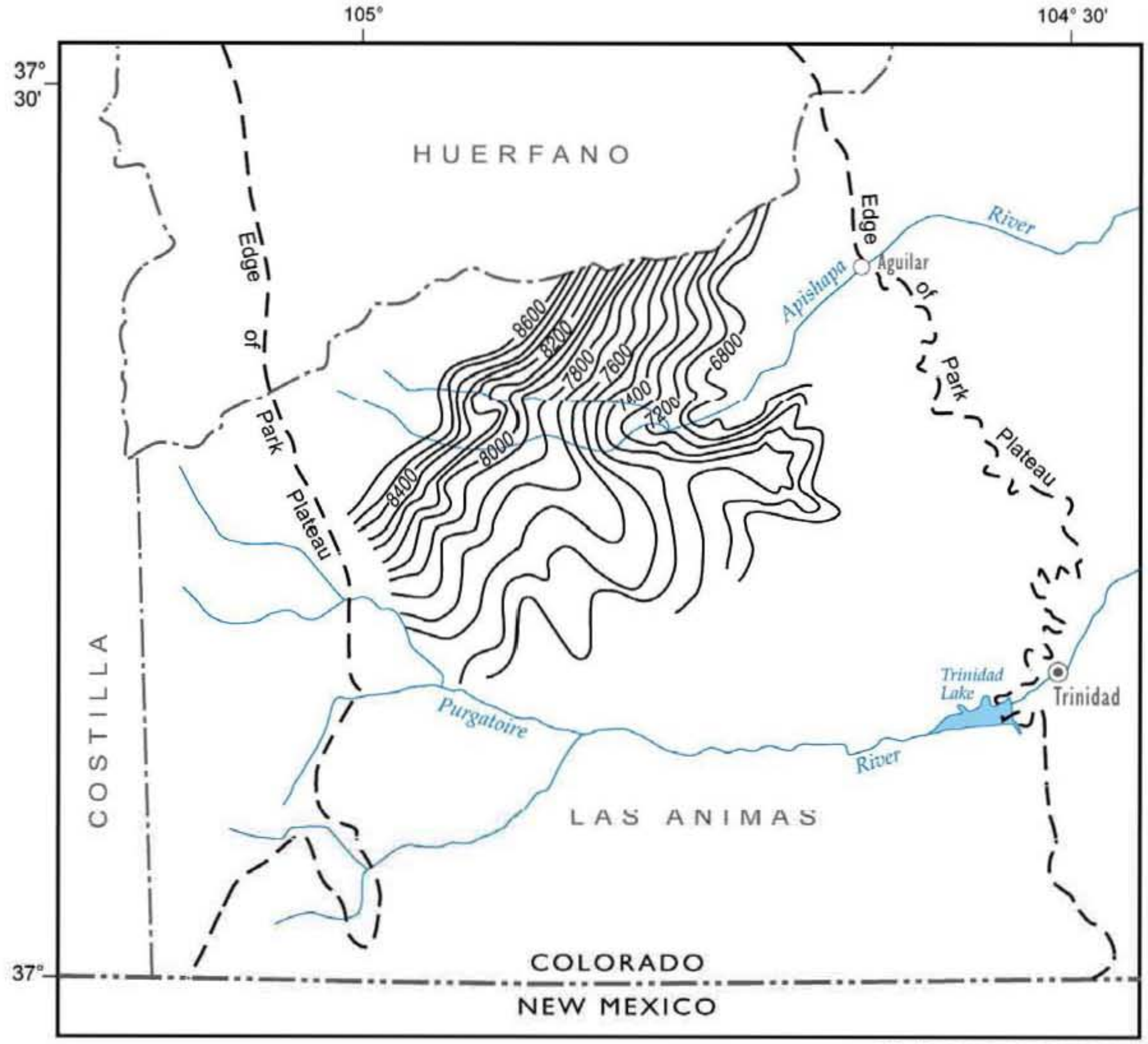


Figure 5.1 Long-Term Average Regional Water Table in the Raton Basin (after Watts, 2006)



Modified from Geldon, 1989

Figure 5.2 Schematic Cross-Section of Ground Water Flow



Modified from Geldon, 1989

EXPLANATION

—7200— Potentiometric surface contour; contour interval—200 feet; datum—sea level

Figure 5.3 Potentiometric Surface in the Cuchara-Poison Canyon Aquifer, May 1978 in the Central Raton Basin

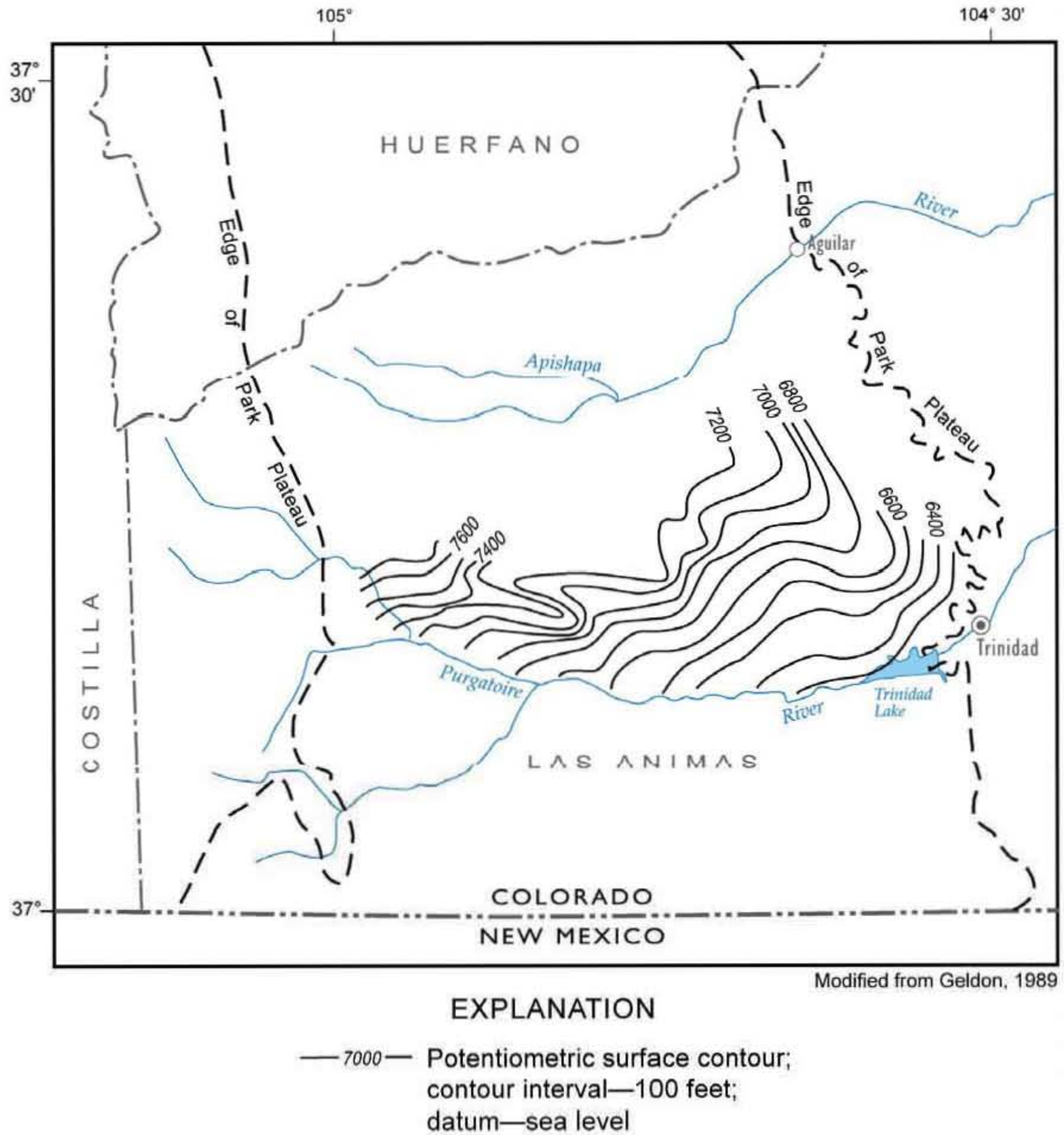


Figure 5.4 Potentiometric Surface in the Raton-Vermejo-Trinidad Aquifer, April-July 1981 in the Central Raton Basin

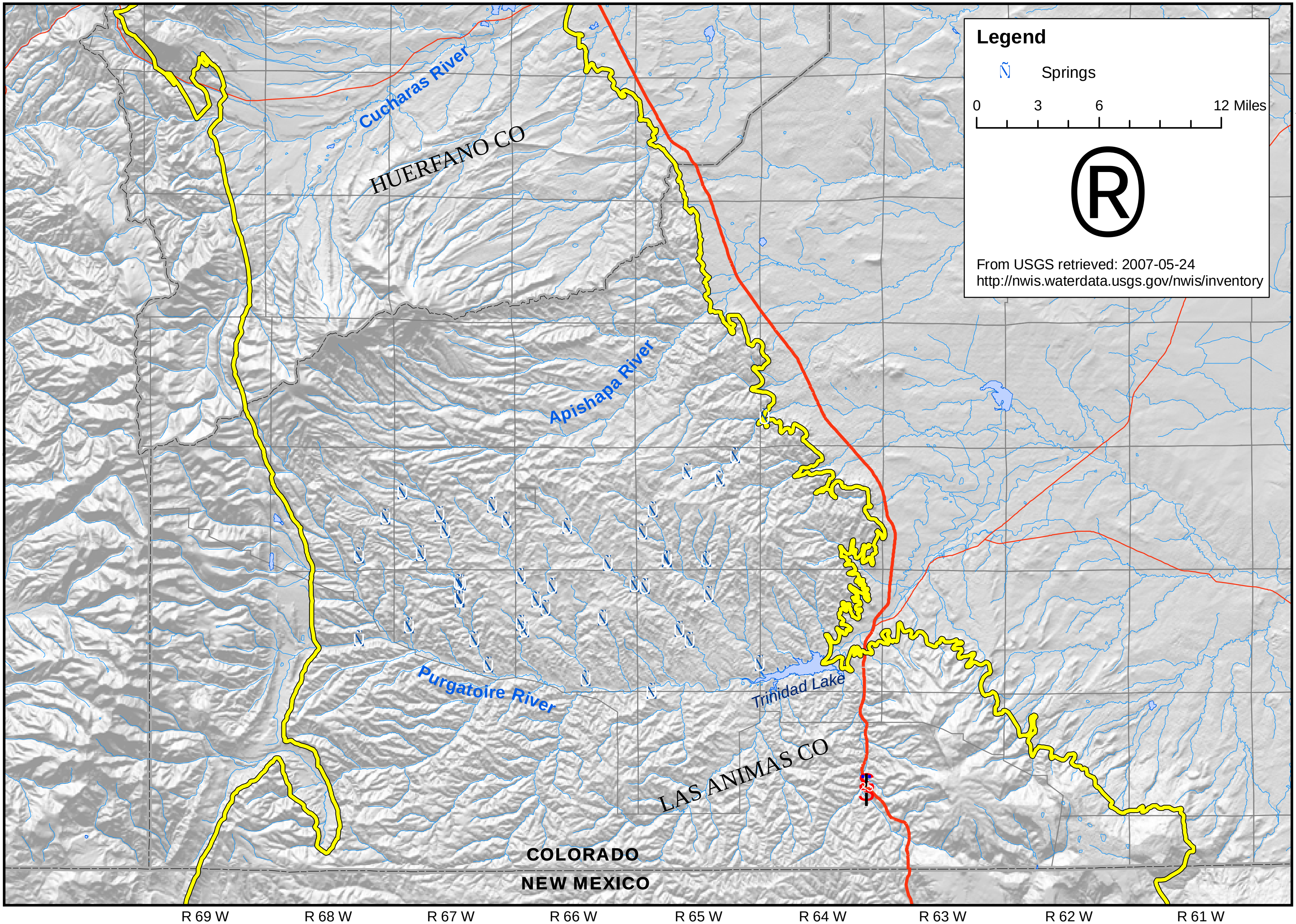


Figure 5.5 Vermejo and Raton Formation Springs

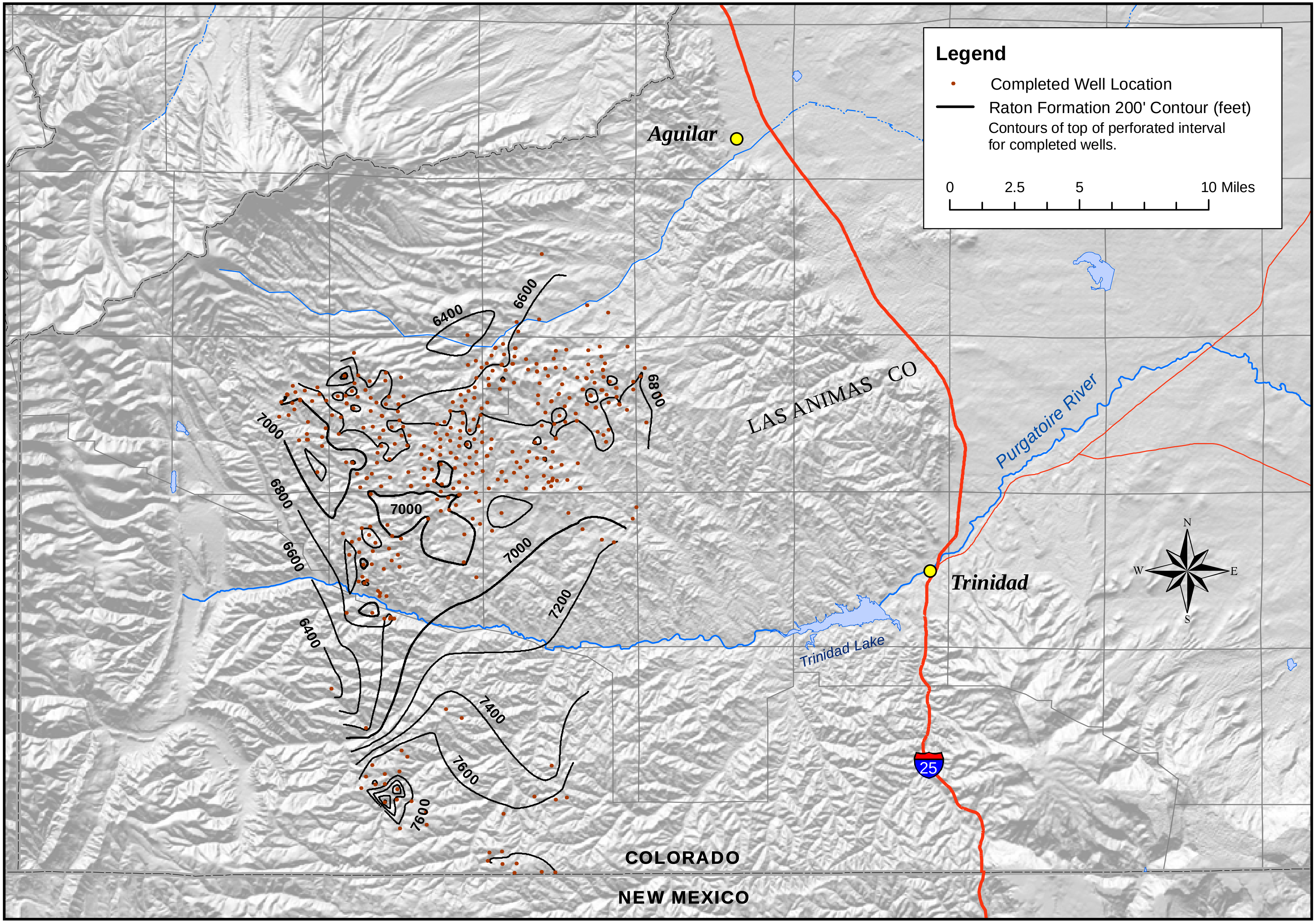


Figure 5.6 Top of Perforated Interval of CBM Well Producing from Raton Formation

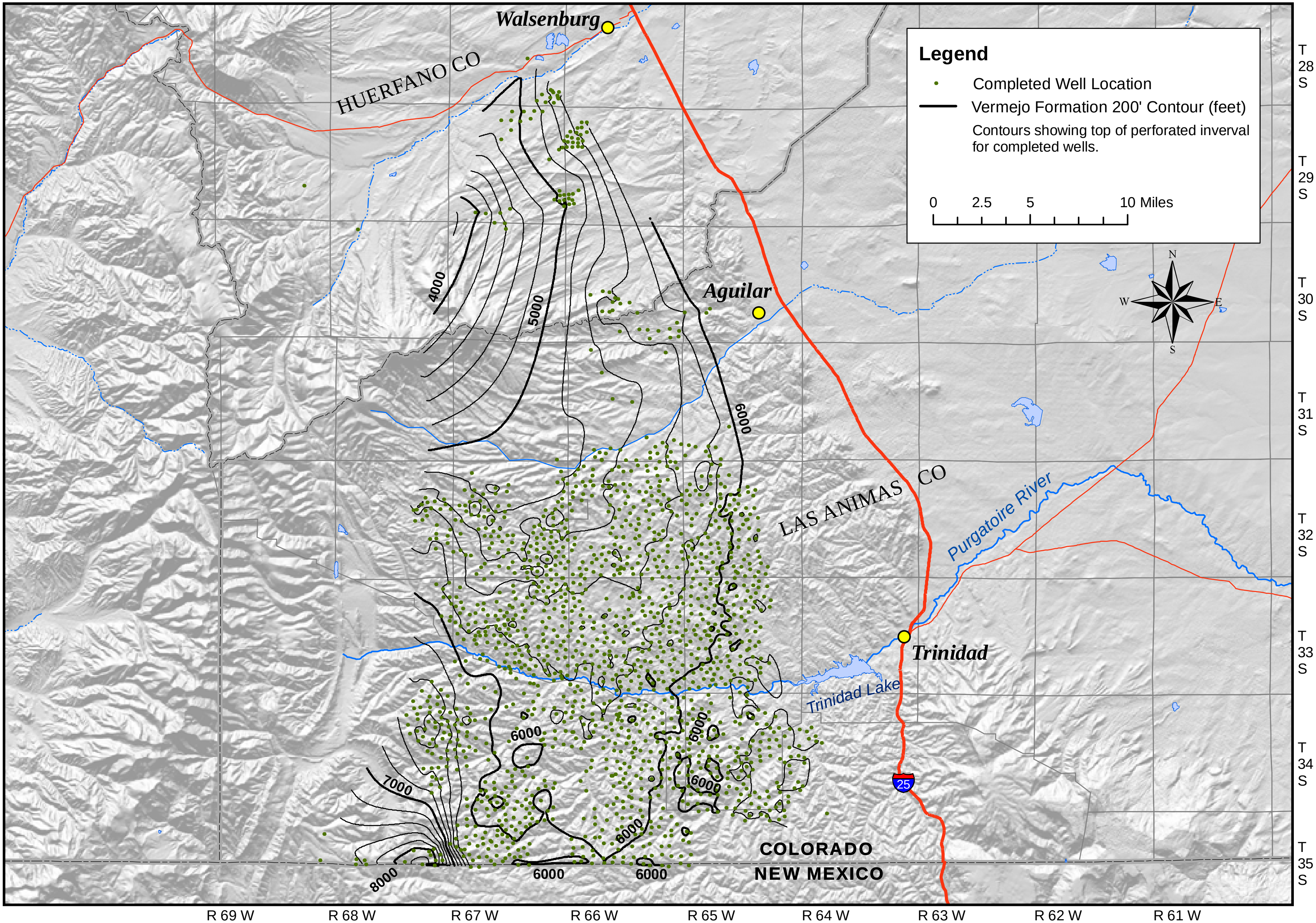


Figure 5.7 Top of Perforated Interval of CBM Wells Producing from Vermejo Formation

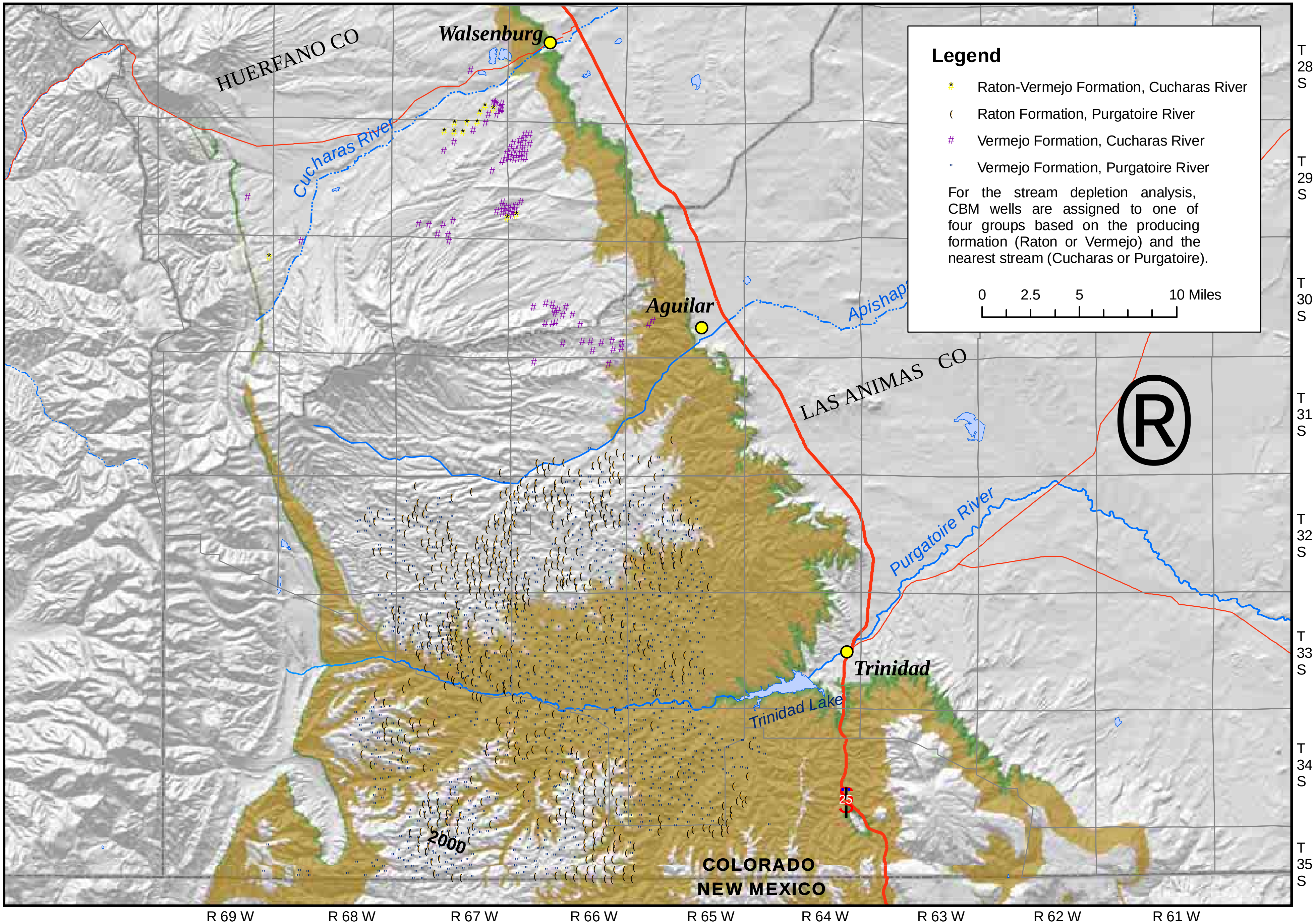


Figure 6.1 Well Groups for Stream Depletion Analysis

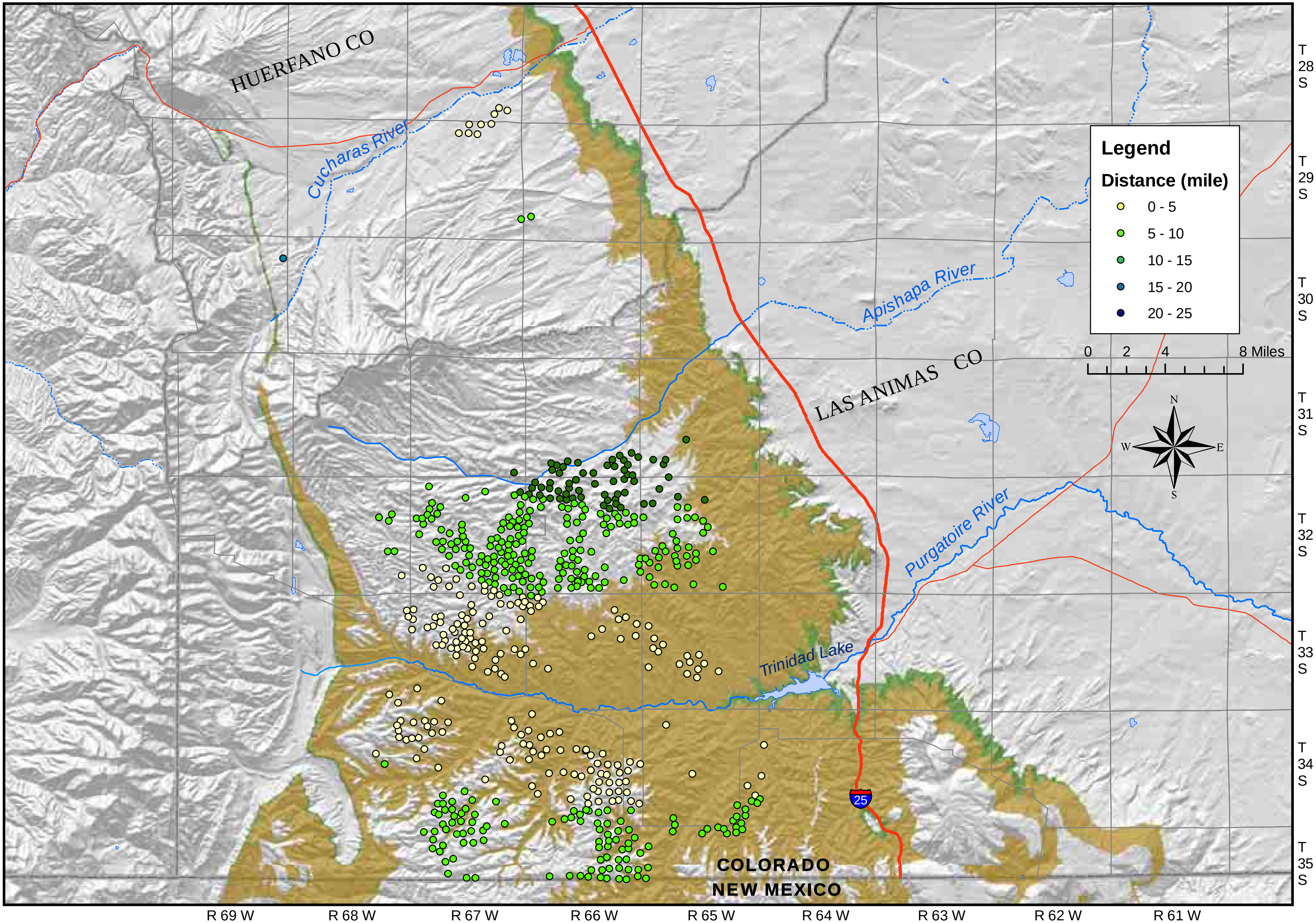


Figure 6.2 Distance to Nearest Perennial River for Stream Depletion Analysis, Raton Formation & Raton-Vermejo Combined Wells

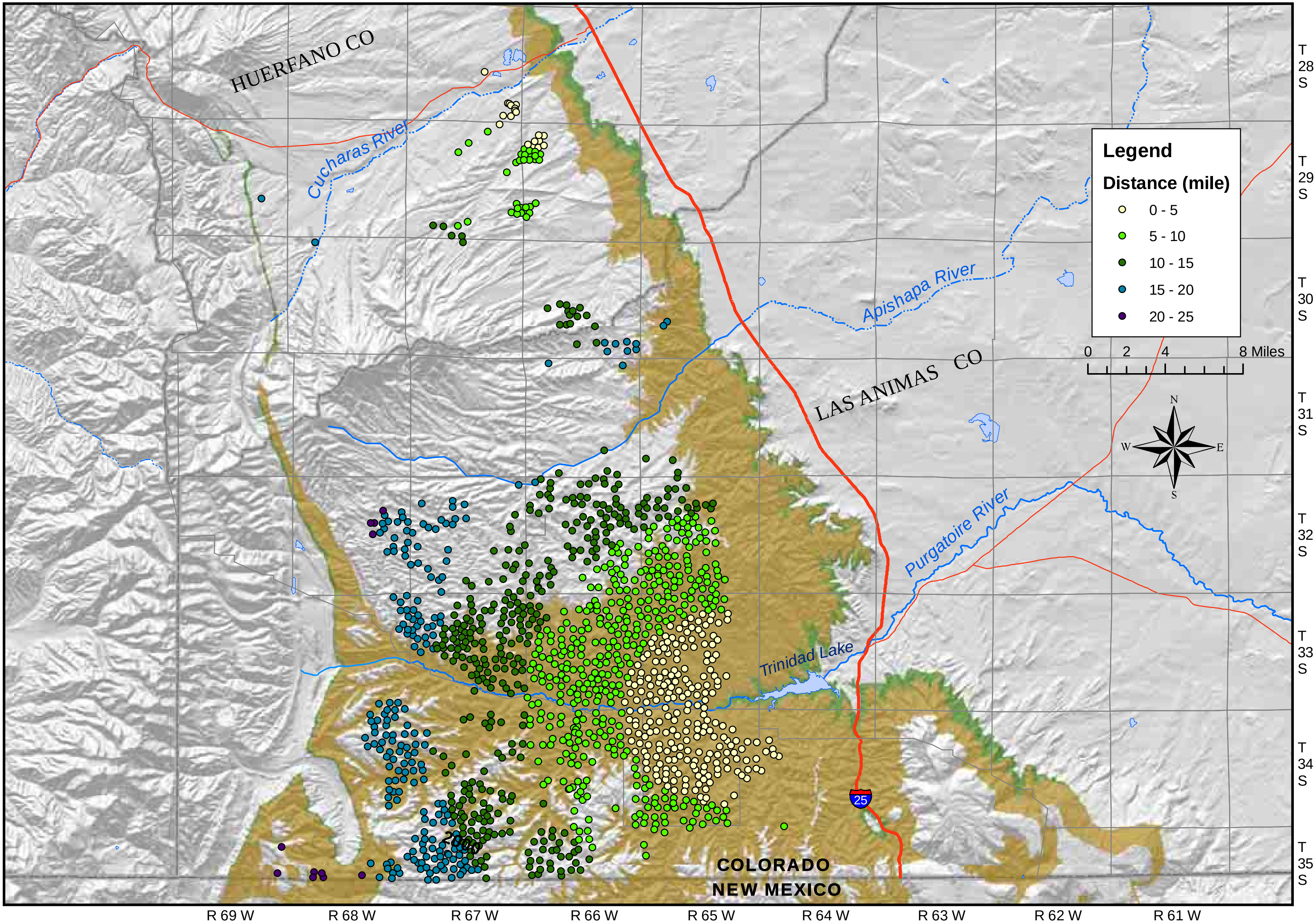


Figure 6.3 Distance to Nearest Perennial River for Stream Depletion Analysis, Vermejo Formation Wells

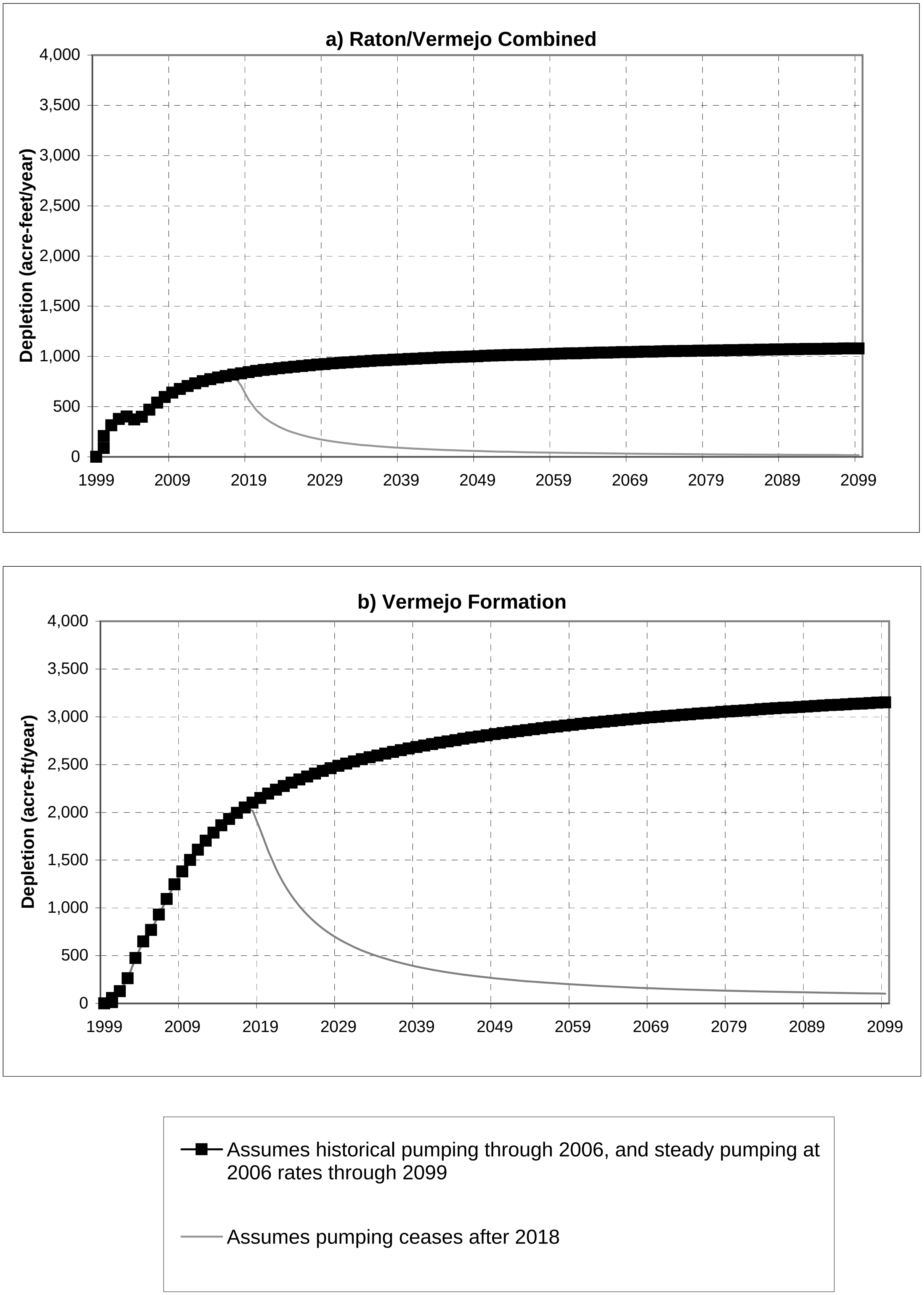


Figure 6.4 Estimated Stream Depletion, Cucharas River

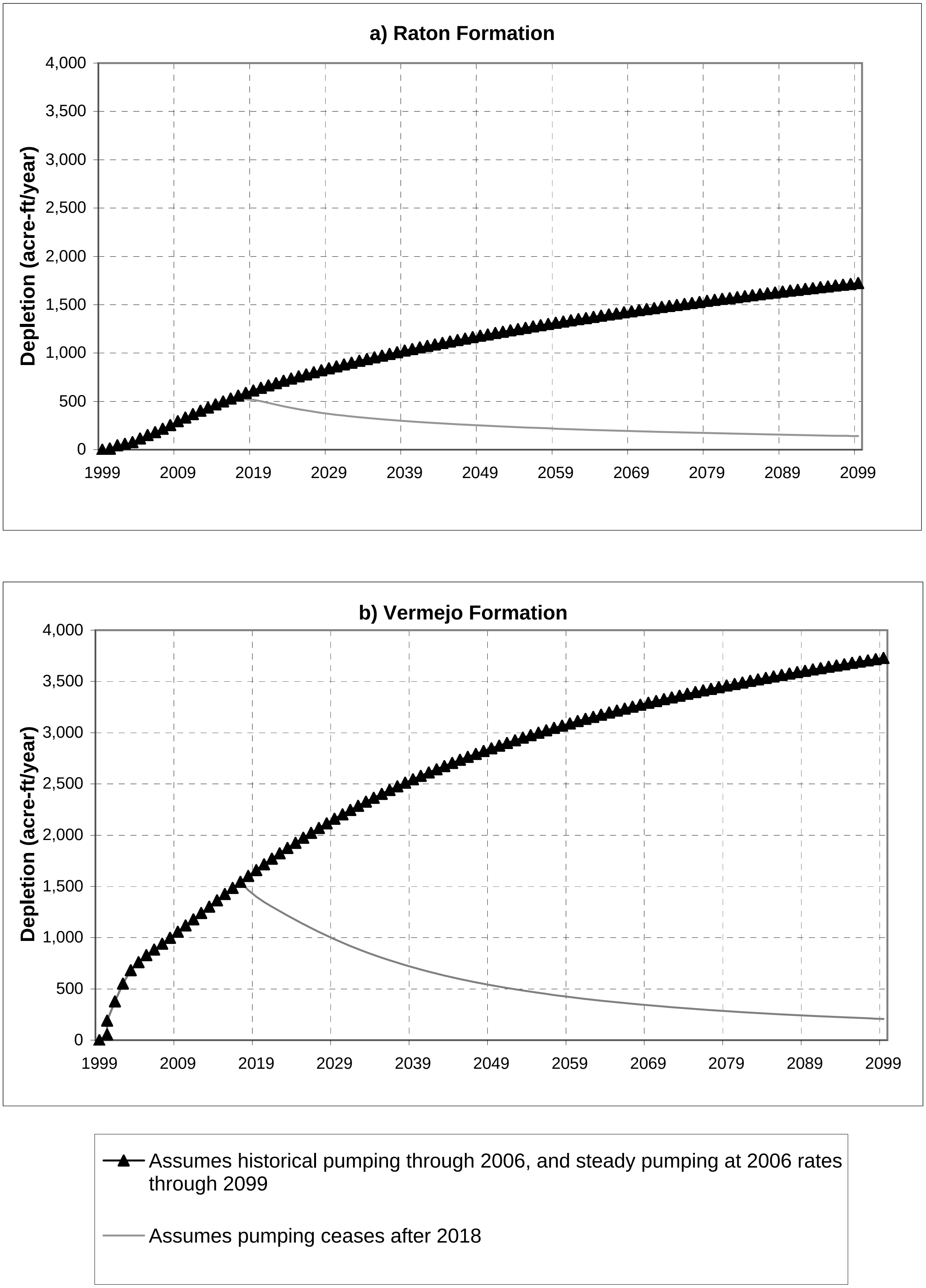


Figure 6.5 Estimated Stream Depletion, Purgatoire River

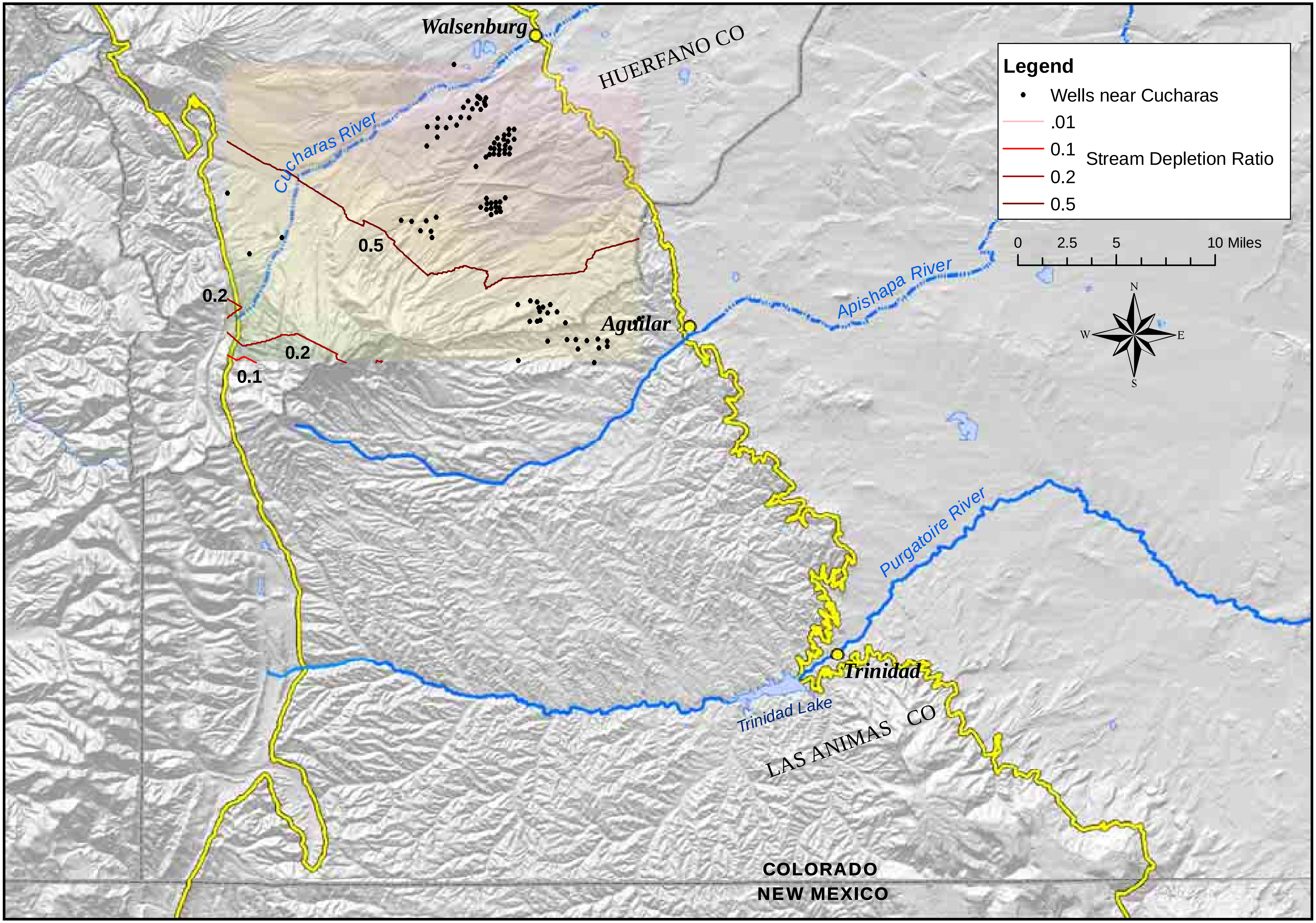


Figure 6.6 Estimated 100-year Stream Depletion as Fraction of Pumping from Raton-Vermejo Combined and Vermejo Formation in Cucharas River Watershed

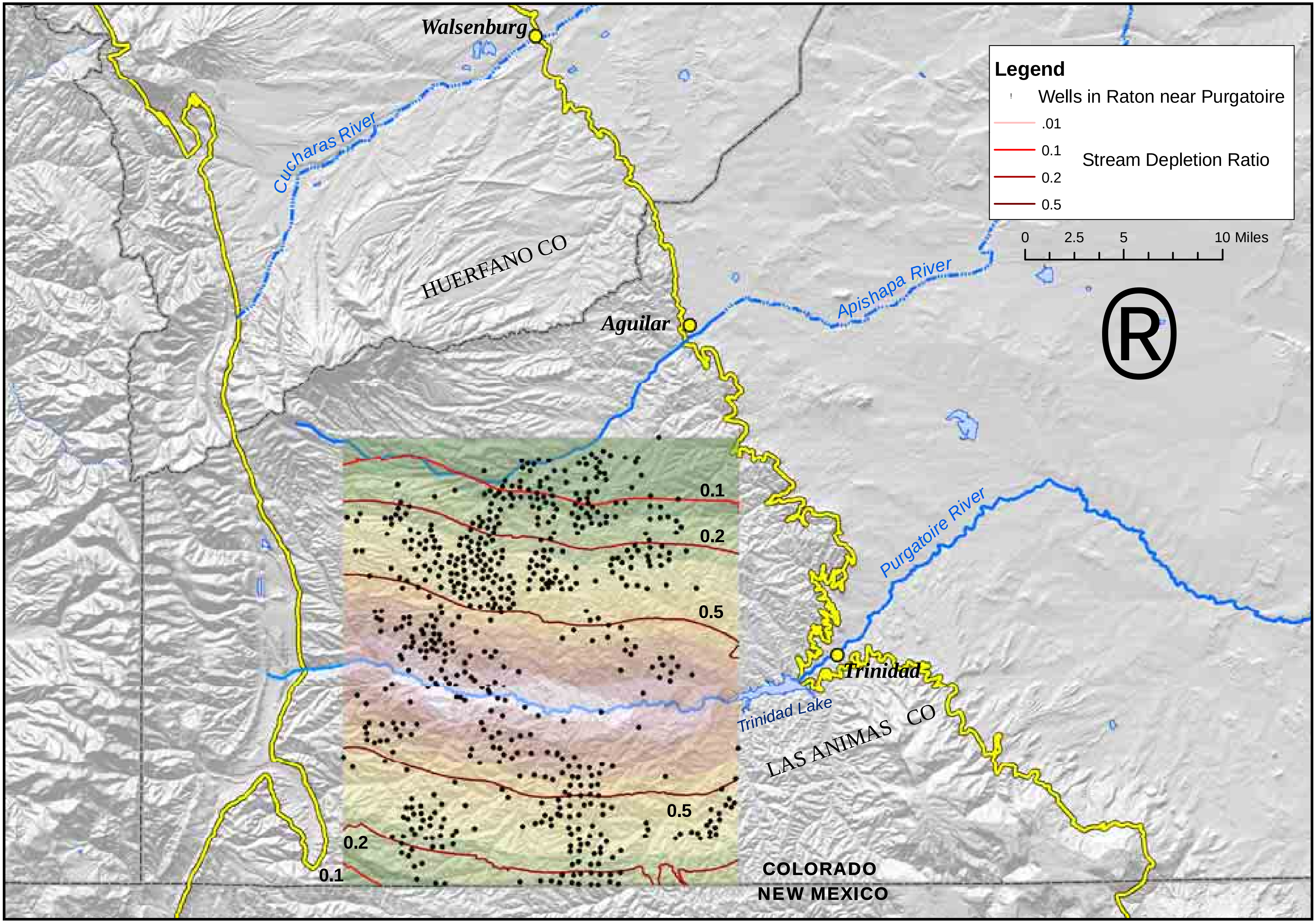


Figure 6.7 Estimated 100-year Stream Depletion as Fraction of Pumping from Raton Formation in Purgatoire Watershed

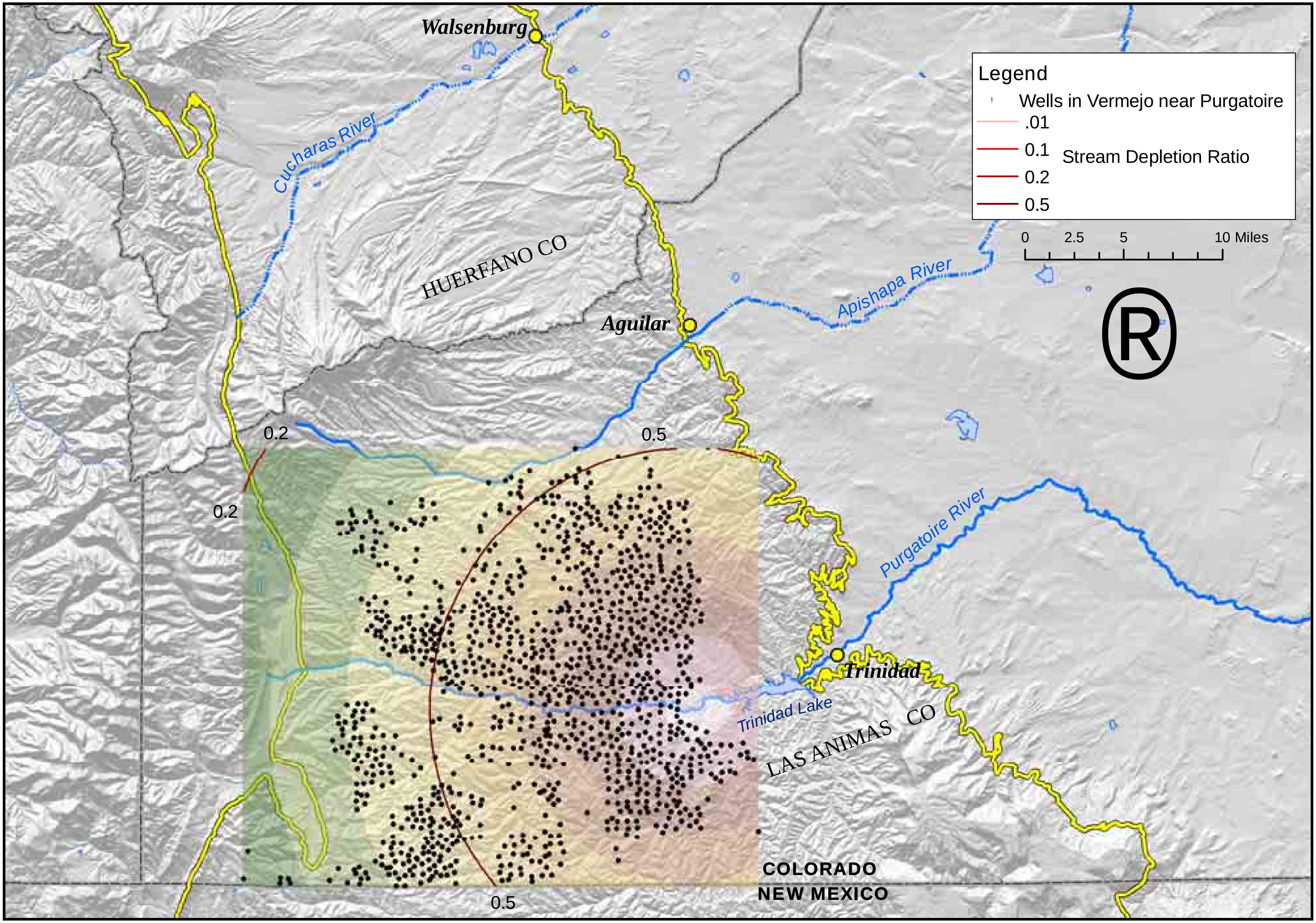
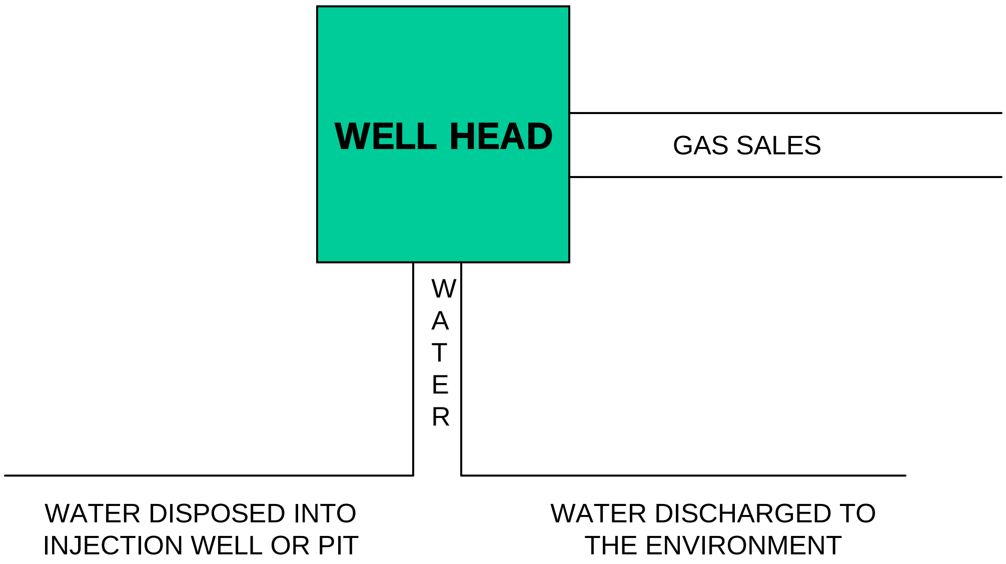


Figure 6.8 Estimated 100-year Stream Depletion as Fraction of Pumping from Vermejo Formation in Purgatoire River Watershed



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.

Figure 7.1 Regulation of Water from CBM Wells

Table 4.1
Average Annual Water Production for CBM Wells in Raton Basin

Year	Number of Producing CBM Wells	Average Annual Water Production per Well (acre-feet)
1999	454	9.5
2000	646	10.8
2001	946	8.9
2002	1119	10.3
2003	1257	10.4
2004	1403	7.2
2005	1665	8.3

Table 5.1
Published Aquifer Properties for the Raton Basin

Aquifer	Specific Capacity (gpm/ft)	Specific Yield/Storage Coefficient	Hydraulic Conductivity (ft\day)		Transmissivity (ft^2/day)	
			Range	Mean	Range	Mean
Alluvial						
- Purgatoire	12		0.014 - 1,880	470	0.14 - 4.2	1.5
- Huerfano	23	0.04	187	-	4,680	-
- Apishapa	16		0.16 - 4.3	1.78	0.78 - 13	6.52
- tributaries	2.2		0.026 - 82	18	0.13 - 570	150
Cuchara-Poison Canyon	0.07	0.0004 (1)	0.062 - 15	3.2	0.20 - 575	52
Raton-Vermejo-Trinidad	0.24	0.0003 (1)	0.002 - 45 (2)	2.2 (2)	0.019 - 215	20

Data compiled from Geldon, 1989. USGS Water Supply Paper 2288

(1) Geldon reports that these estimates are based on similar Denver Basin aquifers
(2) Based on 26 tests, including one test of a 2-foot interval of fractured siltstone (Geldon and Abbott, 1985). Excluding this value, the mean hydraulic conductivity is 0.49 feet/day

Table 6.1
Water Production Volumes for Stream Depletion Analysis

Well Group	Producing Formation	Nearest Perennial Stream	Annual Water Production, afy							
			1999	2000	2001	2002	2003	2004	2005	2006*
1	Raton-Vermejo	Cucharas River	794	1024	1016	912	769	423	950	1265
2	Vermejo	Cucharas River	742	1571	2075	3490	4795	1947	3616	3970
3	Raton	Purgatoire River	642	1340	1594	2389	2573	2691	3442	4535
4	Vermejo	Purgatoire River	2116	3048	3757	4781	4956	5008	5823	6394

* 2006 total volume is estimated based records available at the time of the analysis

Table 6.2
Aquifer Parameters Used for Stream Depletion Analysis

Well Group	Producing Formation	Nearest Perennial Stream	Transmissivity, ft^2/day	Storage Coefficient
1	Raton-Vermejo	Cucharas River	230	2×10^{-3}
2	Vermejo	Cucharas River	230	2×10^{-3}
3	Raton	Purgatoire River	60	4×10^{-3}
4	Vermejo	Purgatoire River	45	3×10^{-4}

Table 6.3
Sensitivity Analysis Summary

Model	Change required to trigger DNR tributary criteria at specified distance		Approximate distance to most-distant CBM wells from stream intersection with formation
	Multiplier, T	Multiplier, S	
Raton-Purgatorie	0.33	Unchanged	12 miles
	Unchanged	> 2.5	12 miles
Vermejo-Purgatorie	0.10	Unchanged	20 miles
	Unchanged	10	20 miles
Raton/Vermejo-Cucharas	< 0.10	Unchanged	15 miles
	Unchanged	> 5	15 miles

Appendix A

Comments Provided to Study Team Subsequent to Public Meeting

From: Debbie Hathaway [dhathaway@sspa.com]
Sent: Friday, May 11, 2007 6:46 PM
To: 'Jerry.Jacob@pxd.com'
Cc: 'bgrigsby@sspa.com'
Subject: FW: review of draft
Jerry,

Under the schedule we have developed with the COGCC and DNR, we will be finalizing an internal draft with their input during the month of June. After June 30, the report will be released by the agencies for review by other parties.

Although it is late in our project, we would continue to welcome any information, or general observations/comments, that the hydrologists you reference would like to provide for our consideration, particularly if they have access to any hydrologic data (i.e., pressure tests, shut-in pressures, water level/pressure monitoring data, aquifer test results, etc.) that are not presently in the public domain.

We look forward to data and insights that you may provide, either in the near future so that we may consider it in preparing the report, or when the report is released.

Deborah L. Hathaway, Principal
S.S. Papadopulos & Associates, Inc.
303-939-8880

From: Jacob, (Gerald) Jerry [mailto:Jerry.Jacob@pxd.com]
Sent: Tuesday, May 08, 2007 10:32 AM
To: bgrigsby@sspa.com
Subject: review of draft

Bryan,

Sorry but I don't have an email for Ms. Hathaway so I'm forwarding this request to you. I've talked with various COGA members and we're in agreement that we would like to provide comments on the draft stream depletion reports for the Piceance and Raton Basins that are scheduled to be released by May 31, 2007. Comments will be provided by several professional hydrologists so it should be a good, high quality peer review process.

It is my understanding that the final reports for the Raton and Piceance basins will be released by June 30, 2007. We would like to get our comments to you as soon as possible after the draft report is released. If you'd like to send an electronic version of the report to me I can ensure that it is distributed to COGA members.

Thanks for your assistance with this. Please advise when you expect to release the draft report for review.

Gerald (Jerry) Jacob, Ph.D.
Environmental and Regulatory Manager
Pioneer Natural Resources USA Inc. - Denver Office
303-675-2646

From: Balleau Groundwater, Inc. [balleau@balleau.com]
Sent: Tuesday, February 13, 2007 3:25 PM
To: Deborah L. Hathaway
Subject: FW: Raton CBM

Attachments: final memo.pdf; Figures.pdf
Debbie H.,

My outline of CBM impacts on the interstate stream of Chicorica Creek is attached for your reference. Please let me know if you find anything on this area in your study, or call to discuss any of this. Thanks.

Pete Balleau
Balleau Groundwater, Inc.

From: Bryan Grigsby [bgrigsby@sspa.com]
Sent: Thursday, February 08, 2007 1:01 PM
To: Jerry.Jacob@pxd.com
Cc: 'Topper, Ralf'; Deborah L. Hathaway
Subject: FW: Raton Basin Stream Depletion Study

Jerry,

Thanks for your interest. We are interested in working with you in any way that we can with regards to acquiring information for the Raton Basin CBM stream depletion assessment study.

Specific information we are interested in obtaining is provided below:

- API number for any well that information is provided for (for wells in Colorado our database lists well name, location, and construction information associated with each API number).

- Permeability test results from drillstem or other tests.

- Well pressure results (shut-in pressures and operating pressures).

- Pressure results from monitoring--or shut-in production--wells. (Wells with a long history of readings would be especially helpful.)

- Anecdotal information regarding behavior of the producing formations (e.g., pressure reduction and/or recovery characteristics)

Also, if Pioneer has similar information for wells in the Raton Basin in NM, we would need formation tops and bottoms, coal intervals, perf intervals.
Obtaining this and water and gas production information for wells in NM is beyond the scope of our work, but we could potentially use pressure and permeability data from those wells to improve our analysis.

If it would be appropriate, we are willing to come to Denver to meet with you to discuss this information.

Let me know if this is sufficient you or if you need anything more from me.

Thank you,
Bryan Grigsby

From: Jacob, (Gerald) Jerry [mailto:Jerry.Jacob@pxd.com]
Sent: Wednesday, February 07, 2007 1:25 PM
To: bgrigsby@sspa.com
Cc: Adam Bedard
Subject: Raton Basin Stream Depletion Study

In response to the recent meeting in Trinidad, can you provide me with a list and layman's description of the data you're trying to gather as part of the modeling effort for the Raton Basin stream depletion study.

Gerald (Jerry) Jacob, Ph.D.
Environmental and Regulatory Manager
Pioneer Natural Resources USA Inc. - Denver Office
1401 17th Street, Suite 1200
Denver, CO 80202
303-298-8100

From: polarsolar [mailto:polarsolar@hughes.net]
Sent: Wednesday, January 31, 2007 11:42 AM
To: boulder@sspa.com
Subject: CBM Water Impacts in Raton Basin

Hello Bryan,

I attended the "Raton Basin CBM Stream Depletion Study" meeting in Trinidad last week. I am a landowner on the North Fork Ranch in western Las Animas County. Two years ago, we encouraged all of the people on the ranch with domestic water wells to get them tested for a baseline record, prior to the onset of CBM extraction. I think we have about six records from that time, including static water levels. Since the onset of CBM extraction, all the static water levels have dropped to varying degrees, but I wanted to point out two in particular.

Last summer there was an "accident" in the drilling of the Molaki CBM well, immediately adjacent to the North Fork Ranch to the east. A bit got stuck. In attempting to free it, a coal seam was blown out into the aquifer that two families draw their domestic water from. Both domestic water wells were impacted. One spewed out contaminated water in geysers 3' - 4' high for several days. It is a very long and unfinished story, but the bottom line is that both of those wells have now run dry. The higher aquifer has obviously drained down to a lower level. The "communication" between aquifers was documented in a study compiled by Applied Hydrology, paid for by Pioneer Natural Resources.

Data will ultimately be available for your study, but since this may well result in a class action lawsuit, it is probably not available at this time. We landowners on the North Fork Ranch believe (with obvious significant supporting data) that ultimately all of our domestic water wells will be destroyed by the ongoing CBM activities.

In preparation for what we knew was coming, the North Fork Ranch spent $50,000 developing Surface Use and Easement Agreements (SUEA) with both of the operators on the ranch. While we were able to get them to take responsibility for water quality impacts, neither would agree to taking responsibility for water quantity impacts. Despite having a high power law firm in our corner, there was nothing we could do to force them to take responsibility. Exactly what we feared has now come to pass - and there was not anything we could do to prevent it. How is this possible?

I realize that impacts to domestic water wells are well outside of the scope of the stream depletion study, but it is clearly related. We landowners feel positively under attack, with no one to turn to for help. The COGCC has continually downplayed the severity of the impact to the water wells, obviously echoing the sentiments of the operator responsible. At this time, there is no regulating agency that puts the environment and the public health and safety foremost. It is all about the money.

Given this information, I urge you to carefully consider the implications and to produce the most conservative report possible. Left unchecked, the CBM industry is likely to render this entire region uninhabitable due to higher level aquifer destruction, methane seeps, induced siesmicity, and the resulting secondary environmental impacts. Now is the time to enact much more stringent regulations, and you are in a position to make such recommendations.

There is much more that could be told. We have also experienced industrial runoff into our streams (see attached photos). I am available to speak on this matter more fully if this seems appropriate. Feel free to forward this message around to whoever you like. It is all on record.

Sincerely,

Tracy Dahl
719-859-4484

From: TOM MELLAND [TMELLAND@petroglyphenergy.com]
Sent: Tuesday, January 30, 2007 11:54 AM
To: Deborah Hathaway
Subject: Coalbed Methane Stream Depletion Assessment Study for theRaton Basin.

Attachments: Total water prod with 10-12 FL.xls
Deborah
We are currently producing water from 51 cbm wells in Huerfano County. Attached is an Excel file with the total water production since we started the project and also the pressure response in one of our monitor wells. I can assure you that the pressure response is representative of Petroglyph's entire currently developed area (one big tank).

After reviewing, let me know if you would like more data or data in a different format. - twm

Tom Melland (tmelland@petroglyphenergy.com)
Raton Basin District Manager

Petroglyph Operating Company, Inc.
P.O. Box 979, 124 N. Main
La Veta, CO 81055

719-742-5570
719-742-5571 (fax)

From: Daniel Valentine [mailto:valendan@msn.com]
Sent: Tuesday, January 30, 2007 8:34 PM
To: boulder@sspa.com
Subject: cbm river research

Hello. My name is Dan Valentine. I live seven miles southwest of Aguilar, on the Apashapa river drainage. I was able to attend the Jan. 24th meeting, in Trinidad, concerning the depletion of live water by CBM drilling activities in the Raton Basin. Currently I am employed by the state as a Deputy Water Commissioner and will begin water administration on the first of April. I have a fairly good knowledge of historic spring sites, wetland sites, and of course the Apashapa River. If there is anything that I can do to help you in your research I would enjoy doing so.

Thank you,

D.A. Valentine
23085 Rd. 43.7
Aguilar, Co. 81020
Home 719-941-4126
Work 719-846-5900

Email- valendan@msn.com

From: Sares, Matt [Matt.Sares@state.co.us]
Sent: Monday, January 29, 2007 5:37 PM
To: raymond Gorka
Cc: Debbie Hathaway; bgrigsby@sspa.com; Wolfe, Dick; Baldwin, Debbie; Barkmann, Peter; Lindblom, Steven; McElhaney, Dave; Topper, Ralf
Subject: RE: San Juan & Raton Basin CBM stream depletion studies......

Ray,
We are just starting on the Raton and Piceance Basin studies now, so the report will not be available until we get towards the end of the project, roughly June 2007. We will be making lat week's PowerPoint presentation and the Scope of Work available on our web site soon (hopefully next week.

Thanks for your offer of information that might help the current Raton Basin study. If your information can be emailed, please send it to Brian Grigsby of Papadopulos and Assoc (bgrigsby@sspa.com), Debbie Baldwin of COGCC (Debbie.Baldwin@state.co.us), and Ralf Topper of CGS (ralf.topper@state.co.us). If your information is in hardcopy form just send to Brian Grigsby of Papadopulos.

If you are interested, we did a project with the same scope of work in the San Juan Basin last year. The final report is available at http://www.water.state.co.us/pubs/pdf/CMSDA_Study.pdf.

Again, thanks for your offer of information. The study will be better with your help and interest.

--Matt
Matthew A. Sares
Deputy Director, Engineering & Environmental Geology Manager
Colorado Geological Survey
Tel: (303) 866-2073
Email: matt.sares@state.co.us

From: raymond Gorka [mailto:rgorka@petrogulf.com]
Sent: Monday, January 29, 2007 2:59 PM
To: Sares, Matt
Subject: San Juan & Raton Basin CBM stream depletion studies......

Hello, Mr. Sares.

I was at the meeting in Trinidad last week.
Is/are these studies available, and if we have info to add to Papadopulos & Assoc., who do we send to?

Thanks
Ray G

Raymond M. Gorka
Regulatory Compliance Manager
Petrogulf Corp.
518 17th St., #1455
Denver, CO 80202
rgorka@petrogulf.com
www.petrogulf.com

Office: (303) 893-5400 **X** 140
Cell: (303) 748-6438

From: Jacob, (Gerald) Jerry [mailto:Jerry.Jacob@pxd.com]
Sent: Wednesday, January 10, 2007 2:41 PM
To: Sares, Matt
Subject: RE: Public meeting notice for Coalbed Methane Stream Depletion Assessment in the Raton Basin

One of the complicating factors when addressing stream depletion in the Raton Basin is the occurrence of active, on-going drainage from abandoned coalmines into local drainages. Evidence of this contribution from abandoned coal mines can be found in numerous locations in the basin, including near the towns of Bon Carbo and Valdez. Past reports of the USGS have shown that mine drainage can be a significant contributor to stream flows in the Basin.

Gerald (Jerry) Jacob
Environmental and Regulatory Manager
Pioneer Natural Resources USA Inc. - Denver Office

Appendix B

Estimation of Surface Water Depletions from CBM Water Production

APPENDIX B
STREAM DEPLETION ANALYSIS

ESTIMATION OF PARAMETERS

Purgatoire Watershed

Transmissivity and storage coefficient parameters for the Purgatoire watershed were estimated from test data, formation properties, lithology, and structure, as reported in the literature (main text, Section 5.2).

Cucharas Watershed

Information on transmissivity and storage coefficients for the Cucharas watershed is sparse; for example, the area is excluded from Watts (2006a) due to lack of data. However, Petroglyph Operating Company (Petroglyph, 2007) provided fluid pressure data at one monitoring well in their Cucharas field. Using this information with well production information, an estimate of transmissivity and storage coefficient was obtained. A multi-well, variable pumping schedule, Theis analysis was set up to simulate monthly pumping at 46 wells located in the area of the Petroglyph Cucharas field for which single well production data were available in the COGCC database. The 46 wells produce primarily from the Vermejo formation, though about one third of them are reported as screened both in the Vermejo and the Raton. Consequently, this analysis does not distinguish between Vermejo and Raton formation properties, and results represent properties of the "combined" formations.

PEST parameter estimation software was set up to optimize the fit between the Theis code calculated drawdown and the observation data. The model was calibrated to the observation data using PEST, resulting in parameter estimates for transmissivity and storage coefficient.

Water production data from the COGCC database, extracted for the period January 1999 through December 2006, were imported into an Access database. Wells were assigned unique Well ID numbers consisting of concatenated State Code (05), County Code (055 or 071), and Sequence No. Easting and Northing location for each well, in State Plane NAD83 US feet, was obtained. The spatial data allow the Theis program to calculate the impact of pumping each well on the observation well, as a function of the distance between them. Observation data were utilized for the period January 1999 through September 2003, avoiding a period when an apparent data gap occurred.

For the multi-well, variable pumping schedule, Theis analysis, each change in pumping rate at a well, either positive or negative, is incorporated as a new stress, 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, results of pumping from the new incremental stresses are computed. The pumping rate was converted to cubic feet per day, in keeping with the units used in the Theis code.

PEST runs were set up to estimate parameter values that provided the best fit between simulated and observed values. For the Cucharas Basin, the PEST optimized results yielded a transmissivity of 230 feet squared per day with a storage coefficient of 2.3 x 10^{-3} for the combined Vermejo-Raton formation. The observed and simulated pressure changes corresponding to this analysis are shown below.

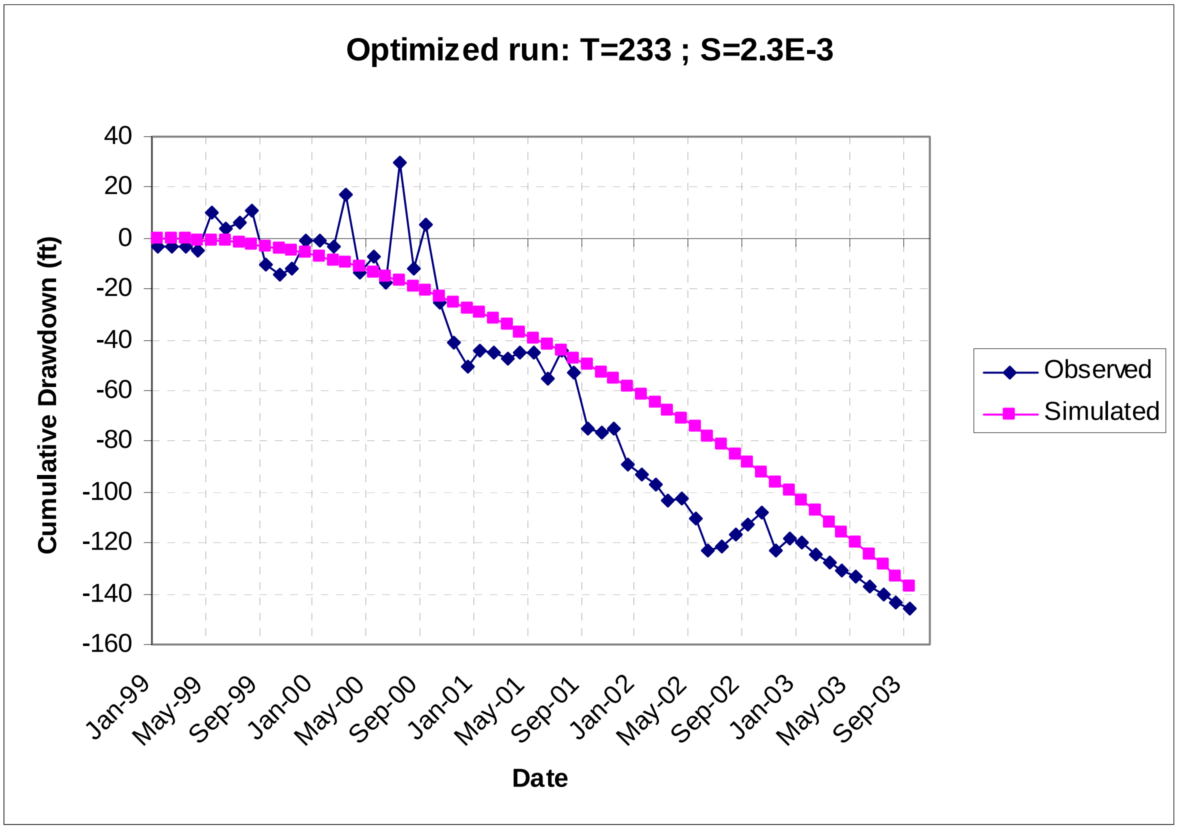


Figure B.1: Observed vs. Simulated Drawdown for Lively 10-12

A sensitivity evaluation was conducted to assess whether over the five-year period used for the parameter estimation analysis, a simple Theis analysis was adequate, or whether, image wells were needed to simulate stream or other boundary effects. For this sensitivity analysis, the impact of one hypothetical image well injecting water at a rate equal to the maximum monthly pumping rate of the combined 46 producing wells was evaluated. The centroid of the pumping wells was located and the vector distance from the centroid to the point where the Cucharas River crosses the Vermejo outcrop was calculated. The image well was located an equal distance from the river-outcrop intersection, projected along the same trajectory. Results indicated that the image well, representing a boundary at the location of the outcrop, would have no significant impact on the drawdown at the observation well within the five-year period used for parameter estimation with the Theis-PEST analysis.

STREAM DEPLETION ANALYSIS

Purgatoire Watershed

Gas and water production data from CBM wells located within the Purgatoire watershed and areas north (to, approximately, the Las Animas county line) were obtained from the COGCC. Data consisted of 596 wells screened within the Raton or combined Raton-Vermejo formations, and 1,162 wells screened within the Vermejo formation; data consisted of monthly values for the 1999 through 2006 period of record. For wells screened in the Raton or combined Raton-Vermejo, distance from the Purgatoire River was calculated; for wells screened in the Vermejo, distance from the well to the point where the Purgatoire River crosses the Vermejo outcrop at the upper end of Trinidad Lake was calculated. Then, for all wells, the calculated distance was used to solve the Glover-Balmer equation for the proportion of pumping drawn from the river, assuming various pumping assumptions over a period of 100 years. Hydraulic parameters were separately estimated for the Raton and Vermejo formations based on hydrogeologic information and test data reported in the literature.

Cucharas Watershed

Gas and water production data from CBM wells located within the Cucharas watershed and south (to, approximately, the Huerfano countyline) were obtained from the COGCC. Data consisted of 12 wells screened within the Raton or Raton-Vermejo formations, and 84 wells screened within the Vermejo formation; data consisted of monthly values for the 1999 through 2006 period of record. For each well, distance from the well to the point where the Cucharas River crosses the Vermejo outcrop was calculated. For all wells, the calculated distance was used to solve the Glover-Balmer equation for the proportion of pumping drawn from the river assuming various pumping assumptions over 100 years. Hydraulic parameters were estimated from a Theis-PEST analysis of production and pressure data, as described above

Appendix C

Cedar Ridge Coal Gas Wells, Tops and Initial Static Reservoir Pressures

Table C-1.
Cedar Ridge Coal Gas Wells, Tops and Initial Static Reservoir Pressures

Well	Good Coal Net Feet	Formation Tops		Elevation at Kelly Bushing	Date of Test	Initial Static			Potentiometric Head (feet)	Location	
		Vermejo	Trinidad			Pressure (psi)	Gradient (psi/ft)	Fluid Level (feet)		T-R	Section
Adobe Canyon 25-11	16	1366	1646	7139	7/15/2000	388	0.241	716	6423	T30S-R65W	25
Adobe Canyon 25-4	12	1310	1576	7060						T30S-R68W	25
Adobe Canyon 30-2	10	1279	1543	7072						T30S-R65W	30
County Line 27-1	26	1716	2003	7428	3/8/2001	367	0.187	119	6309	T30S-R66W	27
County Line 27-3	19	1756	2070	7412						T30S-R66W	27
Luis Canyon 5-2	31	1928	2336	7383						T30S-R66W	5
Mauricio Canyon 1-2	17	1325	1598	6817	2/18/2001	410	0.263	612	6205	T30S-R66W	1
Mauricio Canyon 33-1	19	1662	1982	7258	2/19/2001	437	0.224	940	6318	T30S-R66W	33
Merritt 29-1	12	560	780	6702	1/15/2000	172	0.253	285	6417	T30S-R65W	29
Merritt 29-2	12	606	827	6729	12/1/1999	162	0.235	317	6412	T30S-R65W	29
Merritt 29-4										T30S-R65W	29
Oritz School 34-1	17	1400	1695	7060						T30S-R66W	34
Oritz School 34-3	21	1462	1782	7192	1/23/2001	434	0.246	764	6428	T30S-R66W	34
Oritz School 35-2	17	1482	1792	7240						T30S-R66W	35
Oritz School 35-3	21	1413	1705	7142	3/10/2001	344	0.205	884	6240	T30S-R66W	35
Spring Canyon 20-1	12	1710	2092	7309						T30S-R66W	20
Spring Canyon 20-2	16	1780	2226	7340						T30S-R66W	20
Spring Canyon 21-3	19	1575	1946	7255	11/10/2000	487	0.252	807	6448	T30S-R66W	21
Spring Canyon 21-4	19	1479	1834	7237	3/27/2001	423	0.234	835	6402	T30S-R66W	21
Spring Canyon 21-5	22	1629	2018	7255	3/20/2001	531	0.267	764	6491	T30S-R65W	21
Spring Canyon 22-3	14	1418	1783	7248						T30S-R65W	22
Spring Canyon 22-4	14	1406	1738	7295						T30S-R65W	22
Spring Canyon 28-2	15	1610	2004	7353						T30S-R65W	28
Spring Canyon 29-1	18	1702	2108	7453						T30S-R65W	29
Turcotte 21-1		1478	1866	7185	5/5/2000	442	0.247	771	6414	T30S-R65W	21
Turcotte 21-2	22	1662	2052	7307						T30S-R66W	21
Turcotte 21-3R										T30S-R66W	21
Turcotte 21-4	40	1453	1758	7148	3/29/2000	437	0.252	729	6419	T30S-R65W	22
Wheeler Canyon 35-1	23	1405	1689	7129	3/17/2001	410	0.246	725	6404	T30S-R66W	35
Wheeler Canyon 36-1	10	1452	1720	7152	10/22/2000	405	0.25	688	6464	T30S-R66W	35
Wheeler Canyon 36-2	13	1447	1730	7158						T30S-R66W	35
Wheeler Canyon 36-3	20	1510	1802	7172	10/17/2000	455	0.257	719	6456	T30S-R66W	35
Wheeler Canyon 36-4	21	1360	1676	7049						T30S-R66W	35

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.

COLORADO DIVISION OF WATER RESOURCES
DEPARTMENT OF NATURAL RESOURCES

STATE OF COLORADO 1876

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:

<u>Tributary</u>

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

<u>Nontributary</u>

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.

<u>Not-nontributary</u>

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.

<u>Designated</u>

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.

<u>Geothermal</u>

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.

Appendix E

Reviewer's Comments and Response to Comments

Response to Oral Comments on the Draft Raton Basin Stream Depletion Assessment

Oral Comments, Public Meeting January 4, 2008

Oral comments were received at a public meeting held in Trinidad on January 4, 2008, after release of the draft Raton Basin Stream Depletion Assessment report. The following is a brief summary of the oral comments received at the public meeting with responses.

*1. **Comment:** Lack of discussion of methane seeps in the report:*
An evaluation of methane seeps was beyond the scope of this study. The Colorado Oil and Gas Conservation Commission proactively investigates potential methane seep issues and responds to reports of seeps in the Raton Basin.

*2. **Comment:** Pioneer has two monitor wells on North Fork Ranch, but did not choose to provide the data.*
We could only use data freely offered by the producers; Pioneer did not provide data.

*3. **Comment:** Information provided in the study suggests that aquifers may be depleted and water supply wells impacted, how can this be allowed to happen and what recourse is available to the landowners?*
Evaluation of aquifer drawdown and local impacts to wells was beyond the scope of this study. These concerns are acknowledged. Additional studies are needed to ascertain potential impacts to water supply wells. Please make your concern known to the Department of Natural Resources and your State legislators, preferably in writing.

*4. **Comment:** Who will take responsibility for delayed impacts after the industry leaves the area?*
This concern is beyond the scope of this study but is acknowledged. Please make your concern known to the Department of Natural Resources and your State legislators.

*5. **Comment:** North Fork Ranch has some water quality monitoring data that they can share if future studies of water quality are conducted.*
Acknowledged.

Response to Written Comments on the Draft Raton Basin Stream Depletion Assessment

Extensive written comments were submitted to the authors on the draft report. Responses to these comments are documented below. So that the responses to comments are not lost in the original comment text, the responses have been listed in the first part of this section and indexed as to which page in this appendix the original question/comment occurs. The original comment documents are listed in their entirety in the second part of this section, after the authors' responses.

The following entities submitted written comments on the Final Draft Raton Basin Stream Depletion Assessment:

1. United States Geological Survey
2. North Fork Ranch (Tracy Dahl)
3. Valentine Ranch
4. XTO Energy, Inc. (Martin and Wood Consultants, Inc.)
5. Pioneer Resources and Norwest Applied Hydrology (4 comment sets, submitted by Jerry Jacobs, Michael Day, Seth Okeson and Rick Reinke)
6. TZA Engineers

The comments in their entirety are reproduced in electronic format in this appendix. The comments are addressed in the order noted above. For clarity, commenters will also be noted by the numbers as reflected in the list above.

United States Geological Survey (commenter 1)
General Comment
"*The report provides a good first look at the potential effects of coalbed methane production on stream depletion in the Raton Basin of southeastern Colorado.*"
Agree.

<u>Technical Comments</u>

1 & 2. ***Comment:*** *Commenter questions the use of only one specific pump test for aquifer properties in Huerfano River alluvium.* ***(See USGS page 2)***

Background information provided regarding a literature-reported test included in a general review of literature-reported values (p. 27) is acknowledged. The specific value questioned was not used in the depletion analysis.

3. Comment: *A storage coefficient of 0.003 indicates (a) aquifer thickness of about 3,000 feet or (b) a very elastic aquifer, (c) leaky confining units, or (d) effects of gas exsolution. If pressure drop is substantial, exsolution of gas could also affect the storage coefficient.* ***(See USGS page 2)***

Agree

4. Comment: *Define "semi-confined" within the context in which it is used. ... Semi-confined ground water implies a source of water to the "aquifer" from overlying, underlying, intermingled confining units, or from conversion from confined to unconfined conditions.* ***(See USGS page 2)***

Agree, text clarified.

5. ***Comment:*** *The up-stream deflection of potentiometric contours across the Apishapa River Valley (Figures 5.1 and 5.3) clearly indicate that the Apishapa River Valley is a ground-water discharge area. Whether or not the stream is perennial or intermittent is irrelevant for stream-depletion analysis. When ground-water pumping reduces potentiometric levels in an aquifer adjacent to a stream, it will capture streamflow; increase the capture of rejected recharge (run-off); or intercept ground water that would have discharged to a stream.* ***(See USGS page 2)***

The water level contours are reproduced to provide a general depiction of conditions; however, available data inspected for this study were insufficient to substantiate the occurrence of the "upward deflection" of contours reproduced on the figures. Therefore, a conclusion regarding hydraulic communication was not drawn from the interpretative contours, rather, from other data as discussed in the report. The point regarding stream intermittency related to the existence (or lack of) a base flow that would support the inference of hydraulic communication with groundwater; this observation was not intended to be a presumption of the occurrence of depletion as a function of the nature of stream exchanges, i.e., gains vs. losses. Regardless, the "impacts to the Apishapa", should stream connection be occurring, are not neglected in this analysis; rather, they are transferred to the Purgatoire River. If in fact there is stream connection to the Apishapa, then, the timing of the calculated impacts would occur to a greater degree, sooner, than is presented in the report. However, this would not impact the overall finding of the study.

*6. **Comment:** If flow is generally from west to east (high elevation to low elevation), the area to the east should be a discharge area. **(See USGS page 2)***

It is believed that discharge areas are largely associated with springs and the streams; recharge is greatest to the west in upper watershed areas, hence the direction of groundwater flows generally towards the east. This does not preclude the occurrence also of some recharge on the outcrop areas to the east, and some other flow directions locally that are not reflected on the figures cited.

*7. **Comment:** Ground water is considered tributary if its withdrawal will deplete flow of a surface stream by one-tenth of one percent or more of the <u>rate</u> of withdrawal in 100 years. **(See USGS page 2)***

Suggested wording is more exact; text is changed.

*8. **Comment:** The values for "storativity" of 2 x 10-3 and 4 x 10-3 seem to be about an order of magnitude to large and indicate: (a) aquifer thicknesses of about 2,000 and 4,000 feet; (b) very elastic aquifers; (c) leakage from confining units; or (d) transient effects of exsolution of dissolved gas and desorption of gas from the coal. **(See USGS page 3)***

Agree with the possible explanations for storage parameter of this magnitude. In the Cucharas watershed, this value is supported by the evaluation of data. Likely, the storage parameter is higher than a value computed by Lohman's Rule due to leakage from confining units; this would not be inconsistent with the hydrostratigraphy of the formation. However, if a lower storage parameter were used (i.e., simply based on Lohman's Rule), the depletion would occur to a greater degree, sooner. This outcome would not change the conclusions of the study in terms of the tributary/non-tributary 3 designation, but would be important in that a greater amount of water would be required to offset depletions at a given point in time. Acquisition of more data and refinement of the analyses may be desired in computing amounts of water for offset of depletions, if a situation arises where offsets are required.

*9. **Comment: …**the sensitivity analysis does not consider the effect that a decrease in storage coefficient has. **(See USGS page 3)***

The commenter correctly observes that the sensitivity analysis presented only evaluates changes in parameters that would reduce stream depletion, not increase stream depletion. Thus, the sensitivity analysis presented is more of a "failure analysis" with respect to the study conclusion that pumping within the Raton Basin is tributary. The sensitivity analysis shows how far a parameter combination would need to change in order to invalidate the finding that all areas of pumping within the Raton Basin are tributary. It is correct that if the storage coefficient is lower than assumed, then, the stream depletion impacts would be greater, sooner, than calculated.

*10. **Comment:** I expected to see a more definitive statement about the "suitability of the Glover analysis as a stream depletion analytical tool for administering CBM water production…**(See USGS page 3)***

Acknowledged. The text is augmented with respect to this point in Section 6.3.

Editorial Comments

Comments acknowledged; editorial suggestions have been reviewed and numerous editorial changes have been made.

North Fork Ranch (Tracy Dahl) (Commenter 2)

*1. **Comment:** Methane seeps not addressed. **(See NFR page 1)***

Beyond scope of study.

*2. **Comment:** Other points raised regarding regulation and responsibility for CBM impacts. **(See NFR page 2)***

The comments are acknowledged. Follow up with participating agencies to understand their role and the overall regulatory environment is suggested, as this study's involvement in issues of policy is limited, being largely, a technical study.

Valentine Ranch (Commenter 3)

*1. **Comment:** Recommends explicit modeling of Apishapa River rather than including with Purgatoire. **(See VR page 1)***

Data in this area were sparse; if more detailed studies are conducted in the future, investigators may review this drainage further and represent it explicitly. However, at present, the study conclusion would not be changed by this modification.

*2. **Comment:** Any impact on the Apishapa River is significant due to priority calls. **(See VR page 1)***

Acknowledged.

*3. **Comment:** Springs appear to be drying earlier than usual. **(See VR page 1)***

Acknowledged.

4. ***Comment:*** *Does not know if CBM outflows are affecting Apishapa.* ***(See VR page 2)***

This study did not examine or quantify CBM water discharges to the stream.

5. ***Comment:*** *Recommends evaluating drawdown in wells.* ***(See VR page 2)***

Recommendation is beyond the scope of this study but is acknowledged.

XTO Energy (Martin and Woods Consultants) (Commenter 4)

General Comments

1. ***Comment:*** *The application of the Glover Method is inappropriate for the Raton Basin.* ***(See M&W page 1-2)***

Section 6.3 of the report provides additional perspective on this topic.

2. ***Comment:*** *Glover overestimates depletion as compared to numerical modeling and/or accelerates the timing of impacts.* ***(See M&W page 2)***

Whether one model overestimates or underestimates depletion or timing is a function of the parameterization of the model; and the parameterization is a function of available data. Depending on model details, a simplified analytical model could overestimate or underestimate calculated depletion from a numerical model. More fundamental however, is the question as to whether or not a numerical model would improve the projection of an analytical model. The answer to this question depends on many factors that impact a model's ability to capture the behavior of a system. A numerical model also relies on many simplifications in structure and parameterization. Both modeling skill and a strong data set are required to generate a numerical model that will provide a significantly better answer than can be generated with the analytical model.

3. ***Comment:*** *Geometry of Glover runs:* ***(See M&W page 2)***

Glover requires specification of the distance between a well and the nearest point on the stream. The distance between each well and the point on the stream (as described in Section 6.1.3, p. 37), where the stream intersects the formation of the producing well, was determined using GIS and spatial data for wells available in the COGCC database.

4. ***Comment:*** *Simplifying Assumptions:* ***(See M&W page 2-3)***

These are discussed in Section 6.1.2 of the report.

5. ***Comment:*** *Timeframe for review:* ***(See M&W page 3)***

The comment is acknowledged.

6. **Comment:** The DNR criteria for non-tributary designation is stringent and difficult to satisfy: **(See M&W page 3)**

> Examination of policy considerations or the rationale behind the DNR established criteria is outside of the scope of this study.

Additional page-referenced comments **(See M&W page 3-6)**
1. It is acknowledged that the lower-permeability stratigraphic layers restrict propagation of impacts; this is reflected in the low values for hydraulic conductivity assigned to the model.

2. The water production curves reflect the limited transmissivity of the formations, as modeled.

3. The contributing hydraulic conductivity of shale layers is extremely low and therefore not explicitly represented in the transmissivity; this does not imply however, that the presence of these layers is ignored. There presence is reflected in the delineation of distance to the stream, i.e., the distance is selected laterally within the same formation to the point of intersection of the formation with the stream. Furthermore, is noted that the presence of hydraulic barriers is not supported by the evaluation of data in the Cucharas watershed, nor has sufficient data to support this hypothesis been developed for the Purgatoire Basin.

4. The commenter references Sophocleus, 1995, in support of the claim that partial penetration and stream-bed clogging will cause a model to "drastically overpredict" depletion. In making his calculations, Sophocleous places the well very close to the stream (i.e., 80 meters). In such cases (and also for the relatively short time frames he selected), large differences between Glover and a numerical solution that incorporates partial penetration, clogging, etc, are expected. These factors become much less significant at greater distances and at greater times. McWhorter and Sunada (1981) and Hantush (1965) provide some background on this as are referenced in Section 6.1.2. Unfortunately, Sophocles fails to adequately qualify the conclusion he draws from his fairly specific examples. Furthermore, it is noted that in high energy stream environments such as these located close to mountain fronts, significant stream bed clogging will not exist, and can not persist with the variation in flow levels that occurs seasonally. Finally, regarding the degree of penetration, because the streams being evaluated traverse the entire formation outcrop, there is no horizon of the formation that is not penetrated by the stream.

5. The commenter misunderstands the handling of thickness for the Raton Formation. The 400 to 800 feet of thickness that is eliminated from the transmissivity calculation is the portion of the formation lying above the water table in the upland areas. It is not part of the aquifer. The aquifer thickness used in the model is based on the depth of the water table as reflected in data compiled by the USGS.

Pioneer Natural Resources and NorWest Hydrology (Commenter 5)

This commenter provided four sets of comments, from four individuals, resulting in some duplication of comments. To avoid excessive responses, the salient points are abstracted from the four sets of comments and addressed here.

Pioneer #1: ***Comment:*** *The report provides a preliminary assessment, compiled limited site-specific information that may justify a future more refined estimate of depletion using additional data and more sophisticated tools.* ***(See PNR page 1)***

Acknowledged.

Pioneer #2: ***Comment:*** *The Glover method is inappropriate, being a "50s era method"; there are better more advanced methods available.* ***(See PNR page 1)***

The Glover method is derived from the fundamental groundwater flow equation; which in turn is derived from the principle of conservation of mass and Darcy's Law (1856). Fundamentals of physics have not changed since these processes were articulated in mathematical form. The very same fundamentals are implicit in numerical solutions used in numerical models. The only difference between the analytical and the numerical approach is the size of the unit over which the equations are applied. In the numerical approach, it is possible to apply (an approximation) of the groundwater equations from one user-defined model "cell" to the next, which allows the specification of spatially distributed parameters. As is noted in the report, this approach can yield more accurate results, but only if sufficient data are available to support the specification of spatially distributed parameters. Without data sufficient to support the additional detail, the use of a numerical model won't necessarily provide a better result.

Pioneer #3: ***Comment:*** *The SSPA study neglects heterogeneity; and neglects storage in abandoned coal mines.* ***(See PNR page 1-2)***

See responses above regarding heterogeneity. Regarding storage in abandoned coal mines, conceptually, the computed impacts are those occurring to the line source modeled, which as stated in the report, encompasses the stream and associated water table storage in the outcrop. In turn, any impacts to the outcrop (including the abandoned mines) will accrue to the stream. Regardless, the effect of storage in the mines is not likely significant, as the surface area exposed to the water table would be a small percentage of the overall area for which depletion is calculated.

Pioneer #4: ***Comment:*** *Pioneer offered to meet with study investigators in May 2007 and SSPA did not accept the invitation.* ***(See PNR page 2)***

SSPA requested in the initial public meeting, and in response to subsequent correspondence, that pressure data be submitted for analysis in the study. Pioneer supplied no data in response to this request. An offer to meet with the study investigators as the study was being concluded, to review the study outcome, and evaluate data gaps that emerged, was not responsive to the initial request for data. Data gaps, i.e., the need for pressure data, were clearly identified at the outset of the study.

*Pioneer #5: **Comment:** Future studies using site-specific data may provide a more accurate characterization of stream depletion. **(See PNR page 2)***

> Acknowledged; this was stated in the draft report: "if fluid pressure data and test data developed by all producers were to be made available, the range of uncertainty in calculated stream depletion impacts could be narrowed and more accurate stream depletion estimates could be developed" (ES-2); see also discussions in Sections 6 and 8.

Previous legal determinations should be set forth.
The scope of this study did not include review of legal history; rather, an independent technical determination based on best available data.

*Norwest #1: **Comment:** The SSPA report does not use a correct value for transmissivity. **(See NW page 1)***

> See responses above regarding selected thickness and K values. SSPA evaluated larger scale system behavior in the Cucharas watershed using available pumping and pressure data. This analysis did not support the presence of barriers that would substantially modify the range of values reported in the literature. A similar analysis for the Purgatoire was not possible as operators did not provide pressure data. The analysis of such data was and remains recommended. Lacking this, the study used best available data.

*Norwest #2: **Comment:** The storativity used for the Vermejo formation in the Cucharas watershed is different from that used in the Purgatoire and appears arbitrary. **(See NW page NW 2)***

> The different values relate to the proximity of the formation to the surface and the associated hydraulic communication, see Section 6 of report and previous comments.

*Norwest #3: **Comment:** There are significant impediments to flow between the deeper horizons of the Raton Formation and the Purgatoire River. **(See NW page 2)***

> SSPA had stated that there was "excellent hydraulic communication" between the near-surface horizons of the Raton formation and the Purgatoire River". This phrase is revised to state "hydraulic communication …. is evident." Regardless of the descriptor applied to the hydraulic communication between the near-river zone and the river, SSPA noted (p. 30, draft report) that hydraulic communication to deeper horizons may be impeded to some degree by the presence of shales; however, because the shales are not regionally continuous, there is no basis to infer that communication is precluded between the deeper and shallower zones. Furthermore, because the river traverses the entire section of Raton formation at the outcrop, the transmission of impact need not pass vertically through the section, but may propagate directly within horizons. The hydraulic conductivity assumed for the analysis is 0.5 feet per day. This value for hydraulic conductivity is low – at least two orders of magnitude lower than would be typical for river alluvium or well fractured surficial bedrock material, the materials in

direct contact with the river. Implicit in the application of this hydraulic parameter is an assumption of limited communication to deeper horizons of the formation. Further data and analysis would be required to alternately infer that a greater degree of hydraulic separation is present. Norwest hasn't provided sufficient basis for the study to modify the inferences made from available data as discussed in the draft.

Norwest #4: **Comment:** *The sensitivity analysis is limited; this approach is misleading. Additional graphs and figures illustrating sensitivity output would be desirable.* ***(See NW page 2-3)***

See discussion of sensitivity analysis, commenter #1. The sensitivity analysis was not intended to evaluate all possible combinations of parameters, rather, only to be illustrative of parameter changes that would result in a change of study conclusion. The presentation of additional graphs and plan view figures associated with the sensitivity analysis would not provide additional information relative to the conclusions extracted from the analysis.

Norwest #5: ***Comment:*** *NAH believes that the Glover method is suitable for a screening of the Raton Basin but suggests further modeling work using more sophisticated models be completed.* ***(See NW page 3)***

See responses to previous comments on this topic, and report sections 6.3 and 8.0.

Norwest #6: ***Comment:*** *Representation of the pumped unit as a single layer: the effect of not including vertical communication is to over-estimate the amount of stream depletion over time.* ***(See NW page 5)***

It is understood that the method utilizes simplifying assumptions. The assumptions were applied in the most reasonable fashion to avoid biasing the results by over or under estimation.

Norwest #7: ***Comment:*** *Assumption of perfect hydraulic connection between stream and adjacent materials: neglect or partial penetration and an imperfect hydraulic connection can result in a significant overestimation of stream depletion impacts.* ***(See NW page 6)***

See previous comments/responses.

Norwest #8: **Comment:** *Representation of the outcrop area as a line source; the stream depletion is overestimated by a factor of 200-800 times. (figure 3 and 4 of comments)* ***(See NW page 10)***

Norwest develops an equation for comparison of the portion of water impacting a stream vs. that portion impacting the outcrop and uses this equation with various parameters to make inferences regarding the relative distribution of water obtained from each source. While acknowledging that some of the Glover-computed stream depletion in fact accrues to the outcrop, as stated in the text, SSPA does not concur with the formulation offered by Norwest, with the assumed parameters, or with the conclusions drawn from this discussion in the comment. First, the formulation infers an equality in the head, *delta h*, reflected in the gradient of the stream equation and the head change in the outcrop. In fact, the head change of the gradient driving the stream depletion term is a value appurtenant to the location of the stream, this term represents a maximum when compared to the change in head experienced within the outcrop. The average head change computed for the six miles of outcrop would be significantly smaller than that driving the stream depletion; thus, equating these terms within the formulation is erroneous and results obtained using the derived formulation are incorrect. Secondly, the stream bed conductance term suggested of 1×10^{-4} to 1×10^{-6} per day is considerably smaller that what might be expected for a stream in this high energy environment. For example, if the streambed were considered to be 1 foot thick, the vertical hydraulic conductivity associated with conductance in this range would be calculated extremely low, for example, characteristic of a massive clay. This is not a realistic assumption for this environment, in which alluvial materials are a mix of sand, gravel, and finer-grained materials.

Norwest #9: ***Comment:*** *Difference between analytical and numerical simulations of Petroglyph pumping: numerical modeling of the Cucharas River depletion effects due to pumping at Petroglyph operations indicate that after 100 years of pumping stream depletion effects in the outcrop area of the pumped units do not exceed the non-tributary criteria.* ***(See NW page 11)***

Norwest has not provided a numerical model to the study team; no response to the comment can be made without review of the model described.

Norwest #10: ***Comment:*** *The assumption of a fully-penetrating stream is inappropriate for the Petroglyph site and leads to over-estimation of depletion, similar to that described by theoretical studies and by a model comparison of the Middle Rio Grande Basin.* ***(See NW page 14)***

Regarding the degree of penetration, it is again noted that the stream traverses the entire section of formation at the outcrop, see previous comments. Regarding the Middle Rio Grande Basin, the relevance of that study to this study is not clear. The authors are aware of other basins in which Glover and numerical model analyses have yielded very similar results. However, broad generalizations in this regard aren't considered useful, as each model is impacted by numerous location-specific factors.

Norwest #11: ***Comment:*** *The Cucharas River is shallow and doesn't fully penetrate the aquifer; a partially penetrating stream functions differently from a partially penetrating well.* ***(See NW page 14)***

The investigators disagree with the commenter on this point; however, in any case and as noted in previous responses, the solution will not be highly dependent on the degree of penetration as the Cucharas River crosses the entire sequence of the formation as it crosses the outcrop.

TZA Engineers (Commenter #6)

1. A letter report regarding Hill Ranch is provided with comments; the commenter suggests that this report provides information to show that the area underlying the Hill Ranch should be classified as non-tributary. The study investigators are familiar with the cited report and found no information therein that hadn't been previously reviewed or considered. The study investigators have selected hydraulic parameters that differ from those proposed by the commenter; the rational for the study parameters is identified in the report, Section 5. **(See TZA page 1)**

2. The commenter does not think that the Glover method should be applied to a location with complex geology. Discussion above addresses this perspective. **(See TZA page 1-2)**

3. The commenter states that gradient and water quality data indicate that water is compartmentalized. The investigators acknowledge that water level and water quality data show spatial variability but have not seen evidence of compartmentalization that would preclude the propagation of a hydraulic impact within the formation towards the stream systems. **(See TZA page 2)**

United States Department of the Interior

U. S. GEOLOGICAL SURVEY
Colorado Water Science Center
Southeast Colorado
201 E. 9th Street
Pueblo, CO 81003

December 21, 2007

Matthew A. Sares, Deputy Director, Colorado Geological Survey:

I have reviewed the draft final version of the report "Coalbed Methane Stream Depletion Assessment Study – Raton Basin, Colorado," prepared by S.S. Papadopulos and Associates, Inc. of Boulder, Colorado, in conjunction with the Colorado Geological Survey. Attached with this letter are two lists of comments for your consideration. The first list consists of technical comments; the second consists of editorial comments.

This report provides a good first look at the potential effects of coalbed methane production on stream depletion in the Raton Basin of southeastern Colorado. Thank you for the opportunity to review this report.

Sincerely yours,

Kenneth R. Watts
Ground-Water Specialist

Enclosure

Copy to: Jim Kircher, Director, USGS CWSC, Lakewood, CO
Don Campbell, Associate Director, USGS CWSC, Lakewood, CO
Mike Lewis, Associate Director, USGS CWSC, Lakewood, CO
Pat Edelmann, SE Colorado Chief, USGS CWSC, Pueblo, CO

Technical Comments:

1) **Page 27, 1st paragraph, 2nd sentence:** Geldon (1989, p. 31) states "… an average specific yield of 0.04 (determined from a test of Huerfano River alluvium, referenced in Wilson, 1965, p. 84)." [Reference: *Wilson, W.W., 1965, Pumping tests in Colorado: Colorado Water Conservation Board Circular 11, 361 p*.] This cannot be considered an average because it is based on one test. This test was a 690-minute distance-drawdown test (Theim method) of an irrigation well that was completed in the alluvial aquifer along the Huerfano River in the NW ¼, NW ¼, SW ¼ of section 31, T. 26 S., R. 67 W. The anisotropic and heterogeneous nature of alluvial aquifers may require aquifer-test durations of many days to weeks before a representative value for specific yield can be determined. The proximity of the test wells to impermeable lateral boundaries (the valley is cut into Pierre Shale) and the Huerfano River also may have affected test results but are not documented in Wilson (1965). How was this value used in the stream-depletion analyses?

2) Because the well is located northeast of the Raton Basin and in an alluvial aquifer not considered in your study, you may want to indicate that the specific yield value may not be representative of values for the alluvial aquifers along the Purgatoire and Cucharas Rivers, which are nearer to source areas for the alluvium. Differences in source areas of the alluvial sediments for the Cucharas, Huerfano, and Purgatoire Rivers could cause differences in hydraulic and storage properties of the alluvial aquifers. Typically, there is a down-stream decrease in grain size of alluvial sediments and typically a decrease in hydraulic conductivity and specific yield.

3) **Page 27, 1st paragraph, 3rd sentence:** "Balleau (2006) used a storage coefficient of 0.003…" A storage coefficient of 0.003 indicates (a) aquifer thickness of about 3,000 feet or (b) a very elastic aquifer, (c) leaky confining units, or (d) effects of gas exsolution. If pressure drop is substantial, exsolution of gas could also affect the storage coefficient (*Yager, R.M. ,and Fountain, J.C., 2001, Effect of Natural Gas Exsolution on Specific Storage in a Confined Aquifer Undergoing Water Level Decline: Ground Water, Volume 39, Issue 4, Page 517-525*.)

4) **Page 27, 2nd paragraph:** Define "semi-confined" within the context in which it is used. I know the definitions of confined and unconfined ground water (Lohman, and others, 1972, p. 7). The use of the term indicates that it is because of the proximity of the Raton Formation to the water table. Semi-confined ground water implies a source of water to the "aquifer" from overlying, underlying, intermingled confining units, or from conversion from confined to unconfined conditions. While these could be "vertical" sources of water that reduce drawdown near a pumped well, the effects of pumping at distance, where there is less drawdown, are going to propagate outwardly based on a confined storage coefficient.

5) **Page 29, section 5.2.5.2, next to last sentence:** The up-stream deflection of potentiometric contours across the Apishapa River Valley (Figures 5.1 and 5.3) clearly indicate that the Apishapa River Valley is a ground-water discharge area. Whether or not the stream is perennial or intermittent is irrelevant for stream-depletion analysis. When ground-water pumping reduces potentiometric levels in an aquifer adjacent to a stream, it will capture streamflow; increase the capture of rejected recharge (run-off); or intercept ground water that would have discharged to a stream.

6) **Page 32, last paragraph, 2nd sentence, and figures 5.1 and 5.3:** If flow is generally from west to east (high elevation to low elevation), the area to the east should be a discharge area. [Also see Geldon,1989, figure 54; and Abbott and others,1983, figure 8.1-1]

7) **Page 34, 1st sentenced continued from page 33:** "… may result in stream depletion exceeding 0.1 percent of the pumped quantity within 100 years…" Ground water is considered tributary if its withdrawal will deplete the flow of a surface stream by one-tenth of one percent or more of the <u>rate</u> of

withdrawal in 100 years (*Colorado Division of Water Resources, 2006, Guide to Colorado well permits, water rights, and water administration, March 2006: Denver, Colo., 20 p., accessed March 8, 2007, at http://water.state.co.us/pubs/wellpermitguide.pdf*).

8) **Page 37, section 6.1.4, 1st paragraph, 1st sentence; and page 38, last paragraph:** The values for "storativity" of 2×10^{-3} and 4×10^{-3} seem to be about an order of magnitude to large and indicate: (a) aquifer thicknesses of about 2,000 and 4,000 feet; (b) very elastic aquifers; (c) leakage from confining units; or (d) transient effects of exsolution of dissolved gas and desorption of gas from the coal.

9) **Page 40-41, section 6.2.3:** Although the sensitivity analysis discusses the effects of increasing the storage coefficient on stream-depletion, it does not consider the effect that a decrease in storage coefficient has. If the storage coefficient is smaller (for example, 2×10^{-4} and 4×10^{-4}), the effects of stream depletion will occur much sooner and extend further from the wells. If one assumes that the cone of depression caused by pumping a CBM well expands equally in all directions (the Glover-Balmer stream-depletion analyses is predicated on conditions of aquifer isotropy and homogeneity), then pumping will deplete flows in all streams within the cone of depression.

10) **Page 44-45:** I expected to see a more definitive statement about the "suitability of the Glover analysis as a stream depletion analytical tool for administering CBM water production," which as stated on page 1 is a primary objective of this study and report. The report does state the limitations of the data and the analytical tool but does not state whether the method is or is not suitable. You imply that the Glover analysis is adequate for regional analysis, given limitations of available data and parameter estimates. However, it is likely that producers will challenge the results of the analyses.

Editorial Comments:

[Insertions are indicated by blue underlined text; deletions are indicated by ~~red strikethrough text~~.]

1) **Throughout text** there appears to be an inconsistent spacing between sentences.

2) **Page ES-2, 2nd paragraph, 2nd sentence:** "Applying this criterion, ground water in all areas…"

3) **Page 8, 2nd paragraph, 2nd sentence, and figure 3.1:** The "Wet Mountains" and "Sangre de Cristo Mountains" are not labeled in figure 3.1; "Las Animas arch" in text is labeled "Las Animas Uplift" in figure 3.1; and "Sierra Grande uplift" in text is labeled "Sierra Grande Arch" in figure 3.1.

4) **Page 11, 2nd paragraph:** "Johnson, 1961" is not included in References or should it be "Johnson, 1969".

5) **Page 12, section 3.3.1, 1st paragraph, last sentence:** "Monzolillo (1976)" is misspelled either here or in References, which lists "Manzolillo".

6) **Page 13, section 3.3.3, 1st paragraph, 3rd sentence:** "Orth and others, 1982" is not included in References or should it be "Orth and others, 1981"?

7) **Page 14, 1st partial paragraph, last sentence:** "Flores and Bader, 1999" not included in References.

8) **Page 14, 2nd paragraph, 2nd to-last sentence:** "Hemborg, 1996" is not included in References or should it be "Hemborg, 1998".

9) **Page 20, 1st paragraph and page 21, 1st paragraph:** Reference to "Watts (2006a)".

10) **Page 22, 3rd paragraph:** References "EPA, 2004, Howard (1982), Geldon (1990), and Tyler (1995)" not included in References.

11) **Page 23, 1st paragraph:** "Martin and Wood (1996)", "Balleau (2007)", and "S.S. Papadopulos & Associates, Inc., (2006)" are not included in References.

12) **Page 23, 2nd paragraph:** "… Geldon~~,~~ (1989~~,~~)" and "(Topper and others, "2003)".

13) **Page 23, 3rd paragraph, 1st sentence:** "Geldon (1985)" not in References. Should "~~Geldon (1989 and 1985)~~" be "Geldon (1989) and "Geldon and Abbot (1985)"?

14) **Page 23, last sentence; and page 24, 2nd paragraph:** "Geldon (1985)" not in References.

15) **Page 24, last paragraph, 2nd to-last sentence and page 25, both paragraphs:** "Watts (2006a)".

16) **Page 25, 2nd paragraph:** Petroglyph Operating Company (2007) provided some fluid pressure data at one monitoring well in their field, and associated production data from over 50 wells..

17) **Page 26, 1st paragraph, 2 occurrences:** (EPA, 2004) not included in References.

18) **Page 26, section 5.2.4, 2nd paragraph, 1st sentence:** This is a definition that should be referenced. Suggest (Lohman and others, 1972) "*Lohman, S.W., and others, 1972, Definitions of selected ground-water terms—revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.*"

19) **Page 26, section 5.2.4, 2nd paragraph, last sentence:** Reference to "Lohman, 197~~2~~9" also revise date in References "Lohman, S.W., 197~~2~~9, Ground-Water Hydraulics. U.S. Geological Survey professional Paper708, 70p."

20) **Page 26, section 5.2.4, 3rd paragraph, first sentence:** This is a definition and should be referenced. See editorial comment number 18 for citation

21) **Page 27, 1st paragraph:** Martin and Wood (1996) not included in References.

22) **Page 27, 2nd paragraph:** "…following ~~Lohman's rule for confined storage~~ a rule-of- thumb for estimation of storage coefficient (Lohman, 1979, p. 53) and using a specific storage of 1×10^{-6} ft^{-1} and an assumed saturated thickness…"

23) **Page 28, 1st sentence:** "…noted ~~above~~ previously of 230…" I had to go back three pages to find the value.

24) **Page 28, section 5.2.5.1, 2nd paragraph, 1st sentence:** "… from ~~below~~ less than 10 cfs to ~~above~~ more than 50 cfs…"

25) **Page 32, last paragraph, 2nd sentence:** "…TDS concentrations in CBM produced water tend to fall…"

26) **Page 35, section 6.1.2, 1st paragraph, 2nd sentence:** The last part of this sentence is a conclusion and as such should either be supported by data analyses or references. For a possible source see *Sophocleous, Marios, Koussis, Antoni, Martin, J. L., and Perkins, S.P, 1995, Evaluation of simplified stream-aquifer depletion models for water rights administration: Ground Water, v. 33, no. 4, p. 579-588,.*

27) **Page 45, 1st paragraph, last sentence:** "However, if ~~access can be obtained to~~ fluid pressure and test data can be obtained …"

28) **Pages 46-49, References:** Check references versus citations in text. Several have dates or spellings, which do not agree. As noted in previous comments, several references are missing. In addition, I did not see a citation in the text or figures for Watts (2006b). If Watts (2006b) is not used, delete it and simplify to Watts (2006~~a~~).

29) **Figure 3.1:** See editorial comment number 3.

30) **Figures 3.3 and 3.4:** Indicate that lines of section are shown on figure 3.5.

31) **Figures 4.2 and 4.3:** Add note to define the volume equivalent for a barrel (BBL) and a MCF. For example, 1 barrel (petroleum) = 42 gallons; 1 MCF = 1,000 cubic feet of gas at 60° Fahrenheit and an absolute pressure of 14.73 pounds per square inch. **Check to see if these are the standard conditions used for measurement of gas in Colorado.**

32) **Figures 4.4 and 4.5:** Add date range or end date of accumulation. Add note about volume equivalents of BBLs.

33) **Figure 5.1:** (after Watts, 2006a)

34) **Figures 6.4 and 6.5:** Could you add the ratio (q/Q) on the right-side y axis?

35) **Table 5.1:** Robson (1983) and Geldon (1985) not included in References.

36) **Appendix A:** I did not review Appendix A.

37) **Appendix B, page B-1:** Watts (2006a) and Petroglyph Operating Company (2007).

38) **Appendix B, page B-1:** Need a reference for "PEST."

39) **Appendix B, page B-2:** "storage coefficient of 2.3 x 10^{-3}". Why is this value different from that included in the report?

40) **Appendix C, Table C-1:** Suggest adding a headnote to: 1) Provide approximate conversion of psi to feet of water; 2) explain datum for "initial static pressure"; and 3) explain what the "Gradient (psi/ft)" indicates and provide a conversion to ft/ft or "dimensionless ratio".

41) **Appendix D:** I assumed that this material was verbatim from the DWR and, thus, was not reviewed.

From: polarsolar [polarsolar@hughes.net]
Sent: Monday, December 31, 2007 4:58 PM
To: Debbie Hathaway
Cc: sara j ferguson; Marcia Dasko (E-mail); Amy Dahl
Subject: Raton Basin Study
Hello Debbie,

I have just completed my review of the "Coalbed Methane Stream Depletion Assessment Study - Raton Basin, Colorado". While the statistics and conclusions drawn were quite disturbing, the study itself seems objective and well-researched. To put it succinctly, this appears to be the first credible document pertaining to CBM water issues in Las Animas County. One point that was addressed in the introduction as an area of concern was methane seeps. Unfortunately, I saw no further mention of this now common phenomenon in the rest of the document.

I attended the town meeting in Trinidad on January 24th of 2007, and a message I wrote appears in appendix A of the aforementioned document. I will be attending the upcoming meeting in Trinidad on January 4th in Trinidad as well. Since I was at the previous meeting, I was surprised to find that only one operator in Huerfano County stepped up to the plate to provide hydraulic fluid pressure data. This is especially surprising, since Pioneer has two "monitor wells" located on the North Fork Ranch, where I reside. It was clearly stated several times that a lack of information would result in a more conservative document. There is nothing done or not done by the industry that is not calculated. Evidently, they assumed that the truth would hurt them more than withholding the information.

There are several points from the discussion that I would like to focus on specifically:

5.2.2, p29: Hydraulic heads in deep bedrock aquifers are lower than those in shallower formations. .... downward movement of shallow groundwater to deeper zones may occur.

5.2.3, p33: In summary, the induced fracturing will locally increase formation permeability and may expand the network of flow paths towards more permeable formations.

6.0, p40: Non tributary groundwater is defined as groundwater withdrawn from a well which will not, within 100 years, deplete the flow of a natural stream at an annual rate greater than 1/10 of 1% of the annual rate of withdrawal.

7.3, p50: Results from this study suggest that all areas of CBM production in the Raton Basin of Colorado meet the criterion for tributary designation.

So as a landowner who now finds himself in the middle of the gas fields of southern Colorado, where does this leave me and those like me? While this study did not specifically address domestic water wells, the implications are clear. Our wells are likely to run dry as the underlying aquifers are depleted. There will be numerous people in the audience on Friday who are going to want some answers:

How can this be allowed to happen?

What recourse do we have?

You can't live without water. Should we just abandon our homes, our lives, our dreams?

I realize that this is not really your problem, but I am hoping that someone or some organization can put the pressure on so that our environment and our lives are not destroyed in the name of corporate greed. It is certain that the industry will try to pack the room with employees and contractors, most of whom are not from this area, and will pack up and leave as soon as the boom begins to decline. What will be left behind for those of us who call this place home?

Anyway, thank you for producing this study, even though the conclusions seem to validate my worst fears. I only hope that we have leaders with enough moral integrity to stand up to this industry and hold them accountable for what they are doing. I am not so naive as to believe it can be stopped. As long as there is lots of money to be made, even the most dire of consequences seem to be able to be overlooked.

We have been monitoring the water quality of springs and surface water on the North Fork for about two years now. We also have some data on domestic water wells. If this becomes an ongoing study, we would certainly be willing to share the information with you.

Sincerely,

Tracy Dahl
North Fork Ranch
719-859-4484

Valentine Ranch, LLC
23085 County Rd. #43.7
Aguilar, CO 81020

Jan 10, 2008

dhathaway@sspa.com

RE: CBM stream depletion study in the Raton Basin.

I am a partner on a family ranch on the Apashapa drainage. I believe that combining the Apashapa water shed with the Purgatorie watershed is unwise. I do think that your use of the Glover method is legitimate and prudent. Due to the fact that the local gas industry has been uncooperative in supplying data I suspect that your depletion volume estimates are on the conservative side. More investigation is definitely needed.

Here are my thoughts on the Apashapa drainage:

1) For at least the last fifteen years high priority irrigation ditches have made calls on the system in January or February. Flow volumes recorded on average were certainly higher than 1cfs. These same ditches were shut down usually in November. Due to the fact that the Apashapa River produces lower irrigation volumes than either the Cucharas or the Purgatorie systems any depletion at all is significant.

2) A handful of intermittent springs in the Gulnare area have dried up earlier than usual. These springs supply the Apashapa system as well as stock and wildlife water. In a year, with almost twenty-five inches of moisture in the area, this is highly unusual. Springs that should have dried up in September, or not at all, dried up in early June. Similar springs further from the concentration of gas wells ran as usual. It should be noted that the few springs still running in the area were supplied by CBM outflows.

3) I have not been able to determine the number of CBM outflows affecting the Apashapa. One wonders if they are offsetting any stream depletion.

4) Domestic well draw down should also be looked at. The shallow aquifers and the river system are almost certainly related.

Thank you, for being part of an issue that is of immeasurable importance to Las Animas County.

D.A. Valentine
Valentine Ranch L.L.C.
Aguilar , Colorado

Martin and Wood Water Consultants, Inc.
602 Park Point Drive, Suite 275, Golden, CO 80401
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January 2, 2008

Ms. Debbie Hathaway
S.S. Papadopulos and Associates
3100 Arapahoe Street
Suite 203
Boulder, Colorado 80303

Re: Draft Coalbed Methane Stream
Depletion Assessment Study –
Raton Basin, Colorado
Project Number 730.2

Dear Ms. Hathaway:

This letter comprises our comments and questions on behalf of XTO Energy, Inc., relating to the Draft Coalbed Methane Stream Depletion Assessment Study – Raton Basin, Colorado ("Draft Report").

Our initial comments apply to the overall methodology and approach to determining stream depletions; our later comments apply to specific portions of the Draft Report.

1. The Raton Basin is a highly complex, heterogeneous hydrogeologic setting involving significant structural features, intrusive volcanic features, vertically complex and laterally discontinuous stratigraphic units, confined, semi-confined and unconfined conditions, significant head gradients, and relatively significant topographic features. There are likely three-dimensional ground water flow characteristics within the formations of interest and the stream-aquifer contact configuration involves very minimal penetration of the subject aquifers and, being relatively low energy systems, there is a potential for barriers to vertical flow to exist within the stream-alluvia systems. The Glover methodology was designed for a very simple idealized problem involving stream depletions caused by pumping of an ideal well in an unconfined infinite isotropic aquifer, non-variant stream stages, a fully penetrating linear stream in total and complete hydraulic connection with the aquifer, and a non-variant flat lying water table. The application of the Glover methodology to a system such as the subject Raton Basin aquifers, especially in a case where any resultant determinations may be

utilized in an water rights administrative framework, is inappropriate and the results of these analyses are highly questionable.

2. In our experience in reviewing and comparing the results of stream depletion determinations via Glover and a properly conceptualized, constructed, and calibrated numerical ground water flow model, we have observed two generally consistent trends. First, as the complexity of the system increases and/or the assumptions inherent in the Glover methodology are increasingly violated by the conditions in the real world situation under consideration, the depletion determinations generated by the two methodologies become increasingly divergent. Our experience along these lines has support in the literature. Sophocleus, et al,1995, compared Glover to numerical modeling (utilizing MODFLOW) under increasingly complex scenarios and found that both transverse and vertical heterogeneity (layering) had large effects on the differences between the two methodologies.

Second, and in a situation where a relatively simple system is under consideration, it has been our experience that, while the overall total magnitude of depletions predicted may be similar between the two methodologies, the timing of the depletions is not. Further, it is often observed that Glover will accelerate the depletions as opposed to numerical modeling. Thus, while the overall gross magnitude of depletions estimated over time may be generally in agreement, Glover will tend to over-estimate the depletions at a given time as compared to the modeling results. Sophocleus, et al, 1995, noted in their Summary and Conclusions "In all cases examined here, the analytical solution consistently overestimated stream depletion, thus resulting in more conservative decisions for the cases of equilibrium and nonequilibrium constant- and variable-stage streams in perfect hydraulic connection to the aquifer, irrespective of whether the aquifer parameters are accurately known." This has significant bearing on 100-year determinations of nontributary versus tributary status where an extremely small threshold is being applied (that being the legislatively mandated 0.1 percent "q/Q" ratio).

3. While the Draft Report presents detailed discussions of the background for the Glover runs, including geologic, hydrogeologic, and also presents numerous graphics relating to same, there is not a single specific discussion or graphic representation relating to the actual geometry of any of the Glover runs. The text does verbally describe the points at which the well-to-formation distance was apparently measured, but there is no indication of how the streams were represented geometrically nor what reach lengths were applied.

4. The Glover methodology assumes a zero gradient. From published data on the basin, it is clear that a significant gradient does exist in the basin, from roughly west to roughly east and involving an elevation differential of more than 2,000 feet. While there are the obvious questions as to the consistency of the data (fully penetrating wells?; same hydrogeologic horizons?; local pumping impacts?), such

a large regional gradient would be expected to play a significant role in the overall flow regime, something that cannot be addressed or accounted for via application of the Glover analytical methodology.

5. The Draft Report, while dated "November" and by terms of the original Request for Proposal (RFP PIA-707) was to have been completed by June of 2007, was not to our knowledge released publicly until the end of the first week of December. To have a review period of less than one month during which falls the busiest holiday season of the year does not allow sufficient time for adequate review of this important study whose implications for producers in the basin are significant and widespread.

6. As a final general comment, it is noted that the criterion for determining whether an aquifer at a particular location would qualify as nontributary, that being the 0.1 percent q/Q ratio after 100 years of continuous pumping, is derived from the Denver Basin modeling that was carried out in 1984-1985. The legislature negotiated this arbitrarily derived number and it is very important to keep in mind that determinations within the Denver Basin were made under the benefit of two extremely significant assumptions. First, the aquifers were considered to be at water table conditions throughout and flat lying, and, second, the determinations can thus be made utilizing specific yield of the aquifers as opposed to the vastly smaller storage coefficient. In all areas other than the Denver Basin, actual conditions have to be incorporated into the determination analyses. This means that confined conditions, where they exist, must be applied, including the storage coefficient. When recognizing that a typical confined storage coefficient can be three to four orders of magnitude lower than a specific yield for a given aquifer, the meeting the same 0.1 percent q/Q criterion under such conditions would in all cases be extremely difficult. The conclusion to be drawn is that the Denver Basin derived criterion is simply unrealistic when applied to any other areas of the state and presents an almost insurmountable barrier to obtaining nontributary water outside of the Denver Basin. In the subject Raton Basin, and considering the Vermejo aquifer as an example, it is counterintuitive to have ground water miles from an extremely minimal and limited stream-aquifer contact area be determined to be tributary.

The following comments reference specific page numbers in the Draft Report.

Page 12, Section 3.3.2 In describing the Vermejo Formation, it is noted that the Vermejo is comprised of "sandstones interbedded with siltstones, shales and coal." On page 13, and continuing with the same numbered section and where lateral discontinuity of the coalbeds are discussed it states: "Three main coal-bearing cycles are recorded, with lateral continuity of 1,000 to 3,000 feet." The presence of the shales and lower permeability siltstones along with the laterally discontinuous nature of the coal beds would indicate that vertical flow pathways in this aquifer will be very limited and that the long-distance lateral transmission of head differentials resulting from pumping of water from the producing coal beds would also likely be significantly limited.

Page 13, Section 3.3.3 In describing the Raton Formation, a similar geologic description is presented as for the Vermejo. On the following page, the Raton Formation coal beds are described as "...characteristically lenticular with lateral continuity of 500 to 1,000 feet." The same conclusions as to the vertical and lateral propagation of head differentials as drawn for the Vermejo Formation would be even more strongly applicable with respect to the Raton Formation.

Page 16, Section 4.1 In discussing the production history of the basin, it is noted that "...in CBM wells water production is normally greatest immediately after the well is brought on line." It goes on to note "...a well may have a long productive period with relatively high gas production and little or no water production." These statements reinforce the above observations regarding limited lateral extent of the coal beds and limited head differential propagation. Reviewing the production curves presented in Figures 4.2 and 4.3 of the Draft Report it is immediately noted that the water production curves indicate limited aquifer extent and/or recharge. The production curves do not support a widespread regional aquifer system, a significant connection to the surface stream system, or significant vertical recharge via leakage from overlying formations.

Pages 24-25, Section 5.2.3 In discussing the permeability of the formations and the derivation of transmissivity values to apply in the Glover runs, it is noted that a single ratio of sandstone and coal thickness was applied to the overall formation thickness to develop a transmissivity value. What this does with respect to actual real-world conditions is to remove all the impermeable or less permeable materials from any consideration and thus allows full hydraulic connection between all of the discrete water-bearing zones, something that is clearly not in accordance with the known geology and hydrogeology. This approach ignores the great heterogeneity of the aquifers, the changes in formation thickness relative to producing layer thickness, the potential for very limited stream-aquifer contact, and the presence of interlayer and lateral barriers to flow and head differential propagation.

Page 35, Section 6.1.2 In discussing the limitations and assumptions governing the Glover methodology, and specifically relating to the question of full or partial penetration of the stream, it is stated that "...whether or not the stream fully penetrates the modeled formation has little bearing on the calculated depletion." Sophocleus, et al, 1995, describe just the opposite effect: "Stream partial penetration (we considered 10% penetration) results in significantly reduced stream leakage leading to relatively large discrepancies in the analytical solution." Zlotnik, et al, 1999, also supports this and states "Naturally, the largest values for stream depletion are obtained with the fully penetrating stream model." On Page 36 of the Draft Report, in discussing streambed hydraulic conductivities and the impacts that a low conductive layer at the bottom of the stream could have on calculations of depletions, it is stated "Furthermore, at large times, i.e., more than 10 years, the calculated stream impacts become relatively insensitive to assumptions regarding the permeability of the streambed, regardless of distance." Our experience has been totally at odds with this statement. Extensive depletion modeling in the Denver Basin and the Raton Basin has consistently revealed the streambed conductance to be a highly sensitive parameter, even in simulations involving very large distances (e.g., across all or most of the basin) and incorporating the 100 year timeframe. Sophocleus, et al, 1995, state in their Summary and Conclusions the following: "When the assumption of perfect hydraulic streambed-aquifer connection is removed, that is, when streambed clogging is considered, the departure of the analytical solution from the more realistic numerical solution ranged from significant to dramatic, depending on the degree of streambed clogging." They go on to state "This means that the analytical solution *drastically overpredicts* stream depletion in this case with consequent management implications (emphasis added)." Zlotnik, et al, 1999 further supports these observations concluding "This evaluation also indicates that the stream depletion estimates are very sensitive to the stream leakance parameter..."

When giving this issue more consideration, what must also be kept in mind is the level of violation of the Glover full penetration assumption with respect to the subject study. The Draft Report states that that Raton thickness varies across the basin "in the range of 800 to 1,200 feet over much of the basin interior." From that total thickness there is derived a saturated thickness of "...about 400 feet." Thus, in getting to this point, some 400 to 800 feet of formation material, likely of very low permeability otherwise it would have been included in the "saturated thickness" estimate, has been eliminated. While this in itself raises significant questions as to the applicability of the methodology to the subject problem, of concern in the instant case is the fact that the streams present in the basin are not generally associated with extensive and deep alluvia. With observed stages in the Purgatoire being on the order of a few feet, a comparison to the 800 – 1,200 foot total thickness and even the 400 foot saturated thickness value indicates how far from reality the "approximation" is. If one instead determines that the penetration should be represented by the alluvial thickness (and ignoring the fact that there may well be some flow barrier due to clogging and siltation at the base of the active streambed), the situation improves slightly, but not significantly. A figure of 50 feet is likely a conservative approximation for an alluvial thickness, but still one that pales with respect to 400, 800, or 1,200 feet. To suggest that penetration percentages of 0.25 to 0.37, when comparing the stream stage to formation thicknesses, or 0.75 when comparing stream stage to saturated thickness will have no bearing on calculations of stream depletions is counterintuitive. What is clear is that in the real world situation the connection between the stream and the bedrock formations will involve only a tiny fraction of the formation. With a relatively flat-lying scenario, this would mean only the uppermost layer(s) of the formation would actually be in contact with the surficial system.

In summary, it is our opinion that the Glover assessment carried out, while as per the original scope of the study as defined in the original RFP, is simply unable to accurately characterize the nature and hydraulics of the extremely complex hydrogeologic conditions associated with the subject aquifers. While the study is of value in indicating that there is the potential for hydraulic connection between the coal beds and the surficial stream system, the results of the study are not of sufficient resolution to allow their use in the administration of water rights or in determining actual stream depletions that would be associated with the pumping of water from CBM wells.

Thank you for your consideration of these comments.

Sincerely,
MARTIN AND WOOD
WATER CONSULTANTS, INC.

Phillippe L. Martin, P.G., C.P.G.
Vice President

References cited

Sophocleus, M., Koussis, A., Martin, J.L., and Perkins, S.P., "Evaluation of Simplified Stream-Aquifer Depletion Models for Water Rights Administration", *Ground Water*, Vol. 33, No. 4, July-August, 1995

Zlotnik, V., Huang, H., and Butler, J., "Evaluation of Stream Depletion Considering Finite Stream Width, Shallow Penetration, and Properties of streambed Sediments", Originally presented at the Water 99 Joint Congress – Brisbane, Australia, July 6 – 8, 1999

PIONEER
NATURAL RESOURCES USA, INC

January 14, 2008

Matthew A. Sares
Deputy Director
Colorado Geological Survey
1313 Sherman St, #715
Denver, Colorado 80203

Re: Comments, Coalbed Methane Stream Depletion Study

Dear Mr. Sares:

Pioneer Natural Resources USA Inc. ("Pioneer") appreciates the opportunity to comment on the Draft Coalbed Methane Stream Depletion Assessment Study – Raton Basin, Colorado("Draft Study") authored by S.S. Papadopulos & Associates (SSP). The Draft Study and its methods have already been the subject of extensive technical comments from hydrologic experts. Pioneer is specifically aware of the extensive comments provided by Norwest Applied Hydrology (NAH), a firm with decades of experience in U.S. and international coal bed methane hydrology. The NAH comments submitted apply to the Cucharas as well as the Purgatoire and Apishapa River basins. Pioneer supports the NAH comments and will not reiterate those comments. However, with this letter, Pioneer would like to add its own, more general comments regarding the Draft Study.

Comment #1. Pioneer appreciates the importance of respecting vested water rights and the need to minimize impacts on stream depletion. The Draft Study is a well-intentioned attempt to address an issue of public concern. However, at the outset the report should state that, rather than being a definitive assessment, it is only a "first look" at the issue -- a preliminary assessment, compiled with limited site-specific information, that in itself provides the justification for further study using more sophisticated tools, site-specific data, and analyses that will provide a more accurate and refined estimate of stream depletion.

Comment #2. Pioneer concurs in comments from NAH on the inappropriateness of selecting the Glover methodology, a 1950s era method, to estimate stream depletion across millions of acres of a geologically complex coal basin. Any estimate of stream depletion could have important ramifications for future energy and water policies. There are better, readily available methods available to produce more reliable estimates of stream depletion and to better inform the state's policy-makers. The Draft Study should recognize the value of more advanced models to policy-makers and acknowledge that this work remains to be done, rather than dismissing its usefulness (page 45).

Comments #3. Applied at such a broad scale, the method used in the SSP Study necessarily makes very broad assumptions, to the point where the variability inherent in such an estimate is so large as to make that estimate virtually meaningless. For example, the average parameters used in the analysis for the Purgatoire River do not account for the heterogeneous nature of the geologic formations. Water is produced from many individual coals seams in each well. These coal seams are not continuous across the

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basin. The discontinuous nature of the coals and sandstones along with the many intrusive features (dikes) which lie north and parallel to the river produce a lower effective transmissivity than that used in the analysis. As another complicating factor: the area close to the river has seen extensive underground coal mining. These abandoned mines provide considerable water storage that is not accounted for in the analysis. The SSP analytic method is unable to account for water added back to the groundwater system.

Comment #4. The Draft Study (page ES-2) gives that impression that industry was uncooperative and as a result the accuracy of the stream depletion estimates in the Draft Study suffered. In fact, industry attempted to consult with SSP on its data needs. Many such contacts are reflected in Appendix A (public comments) of the Draft Study. In May 2007 Pioneer, on behalf of several coalbed methane producers, spoke with a representative of SSP to discuss the possibility of SSP getting together with industry's hydrologists to review the current status of the Draft Study and identify the data "holes" uncovered so far. When offered the possibility of having a meeting among SSP, and industry representatives with their hydrologists to better define what data was available and what data could or could not be provided, SSP said that their budget did not allow for this type of meeting. It is therefore unfair and inaccurate to blame the industry for the inherent limitations of a broad study that is admittedly intended to provide an "overview" of a very complex geographic, geologic, and hydrologic system.

Comment #5. Finally, the Draft Study should recognize that other studies and determinations using site-specific data may provide a more accurate characterization of stream depletion in specific locations within the basin. The report should make clear that it is not intended to be preclusive of future more comprehensive and accurate studies. In addition, it is Pioneer's understanding that there have been previous legal determinations concerning the nontributary nature of groundwater in areas subject to the Draft Study. The Draft Study should expressly acknowledge the finality of such legal determinations as set forth in existing water court decrees.

To close: Pioneer believes the Draft Study should explicitly state that the methods employed in the report are only appropriate for use as a screening tool. An evaluation of the tributary status or nontributary status of water-bearing zones in the Basin, and certainly any numerical estimate of depletion, should be conducted with a refined numerical model and better data, and recognize prior determinations.

Sincerely,
For Pioneer Natural Resources USA Inc.

Gerald R. Jacob
Western Division - Environmental & Regulatory Manager

Comments on Draft "Coalbed Methane Stream Depletion Assessment Study – Raton Basin Colorado", November 2007

1. General Approach

The draft study "Coalbed Methane Stream Depletion Assessment Study – Raton Basin Colorado" ("report") used the Glover analysis as directed by the DWR to conduct a stream depletion analysis of current and projected impacts of CBM water production on flow in streams traversing the Raton Basin, specifically, the Cucharas River and the Purgatoire River. Comments on the inherent problems with using the Glover method for stream depletion analysis have been submitted by several commentators on the San Juan basin study conducted by S. S. Papadopulos & Associates ("SSP") (S. S. Papadopulos, 2006). Specific comments on issues with the use of the Glover method for evaluating potential depletion in the Cucharas River basin portion of the Raton basin have been submitted by Norwest Applied Hydrology (NAH) on behalf of Petroglyph (NAH, 2008). NAH concurs with the general comments on the limitations of the Glover method. NAH believes a numerical groundwater flow model can be applied to provide more reliable and more accurate estimates of stream depletion within a complex hydrogeologic setting such as the Raton Basin. However, regardless of the methods that are used for analysis, it is essential that the methods be applied to adequately represent the hydrogeologic setting. The following comments are submitted to point out specific concerns with the application of the Glover method for estimating depletion in the Purgatoire River basin.

2. Model Parameters Chosen by SSP for the Glover Analysis

a. Transmissivity – The Glover method used requires the assumption of a homogeneous aquifer. The report states "*Groundwater movement through a heterogeneous aquifer can be modeled as flow in a homogeneous media through identification of "effective average parameters" that, on the scale of the problem to be solved, will reasonably characterize the aggregate properties of the composite materials*" (page 35 Section 6.1.2). Effective aquifer transmissivity was estimated using hydraulic conductivity values reported by Geldon (1989) and with the assumption the transmissivity is due to the sandstone and coal intervals within the Raton Formation which average 29% of the total thickness (Geldon, 1989 Table 5). While this may be a reasonable approach for a relatively small scale area where 29% of thickness is sandstones and coals that are horizontally continuous across the volume chosen, it ignores the effects of sandstone and coal units not being contiguous across the larger, basin-scale area being examined in the study. Past studies of the Raton Basin indicate the discontinuous nature of the formations effects significantly the flow dynamics of the basin. The Glover method is too simplified to account for these discontinuities in the formations. The SSP report states "*While the Poison Canyon, Raton and Vermejo Formations have different depositional histories and variable characteristics within their various units, all tend to be described as consisting of overlapping, gradational sequences, intertonguing, and lacking in laterally extensive correlative units that would be associated with clear and distinct aquifer designations*" (page 20 Section 5.1). Vertical hydraulic conductivity values are commonly less than a tenth of horizontal values. If the Glover method is being applied at a regional scale (as is the case in the SSP report) it is essential that the transmissivity of the modeled unit be substantially reduced to account for the discontinuous nature of the sandstone and coal units and structural influences at the regional scale that is being modeled. The SSP report does not use a correct effective transmissivity in their analysis.

b. Storativity – The authors used a storativity value for a confined/unconfined system for the Raton Formation and not the Vermejo. In the report, the impacts of CBM pumping on the Vermejo are evaluated at the outcrop, however the formation is unconfined at the outcrop. The report uses a value of 2.3E-3 for storativity of the Vermejo Formation in the Cucharas River drainage based on matching observed field behavior and 3.0E-4 for storativity of the Vermejo Formation in the Purgatoire River drainage. It is unclear from the report why the Vermejo Formation in the Purgatoire River drainage would not have similar storage response as the Vermejo Formation in the Cucharas River drainage. The use of a much smaller storativity in the Purgatoire drainage than one derived from field observations of the same formation within the Raton basin seems arbitrary.

3. <u>Stream-Aquifer Contact, Recharge, and Discharge Areas</u>

SSP asserts that there is excellent hydraulic communication between the near-surface horizons of the Raton Formation and the Purgatoire River. At any given location, where the river cuts through the Raton outcrop, lithologic units within the Raton that are in direct connection with the Purgatoire River and its alluvium may have good local hydraulic connection. However, extension of this connection to the entire thickness of the Raton at all locations is questionable on several counts. First, the river is clearly gaining overall based on the winter baseflows presented in the SSP report for the Stonewall and the Madrid USGS stations. The magnitude of the gain is on the order of 10 cfs using the numbers presented. However, as discussed by Geldon some of this gain comes from outside the basin due to inflow on the north and south forks of the Purgatoire River. The presence of shallow groundwater is not surprising given the river is gaining. Second, Geldon (1989) attributes the existence of springs to infiltrating groundwater encountering less permeable formations which outcrop in the canyons including blockage from Tertiary igneous rocks. This suggests limited hydraulic connection between the shallower horizons and the deeper horizons within the Raton Formation. These factors suggest that the Purgatoire River is hydraulically connected to the fairly small amount of alluvium present in the drainage, that the Purgatoire River gains groundwater from the Raton Formation with the majority of the gains coming from fairly shallow horizons, and that there are significant impediments to flow between the deeper horizons and the Purgatoire River.

4. <u>Sensitivity analysis</u>

The sensitivity analysis portion of the report is limited to examining how much either the chosen transmissivity or storativity could be changed before the groundwater would be non-tributary. This approach is misleading on several fronts. First there are certainly realistic combinations of parameters where portions of the basin would be considered non-tributary using the Glover analysis. For instance if the analysis was done for the Vermejo Formation and the Purgatoire River using the Vermejo storativity derived for the Cucharas drainage and a 10-fold reduction in transmissivity as discussed in Section 2.a of these comments, the non-tributary boundary is approximately 7.5 miles from the river. If an unconfined storage value was used the non-tributary boundary moves much closer to the river/outcrop intersection.

The sensitivity analysis did not show the influence of changing the parameters on the estimated stream depletion fraction. Given the very conservative analysis conducted by SSP, it is imperative to show the uncertainty in the predicted results even with parameters that show the entire basin is tributary groundwater. The effect of varying the parameters used in the Glover method should be shown for both the depletion graphs and the plan view figures showing the estimated stream depletion fraction.

5. Summary

NAH believes the Glover method is suitable for an "initial screening" of the Raton Basin to begin to develop an understanding of the tributary/non-tributary boundary. The modeling community recognizes the limitations of the Glover method and in the case of being applied regionally to the Raton Basin, its usefulness as an accurate analytical tool must be questioned. Given the potential consequences of using such a simplified model to analyze such a complex basin, NAH suggests further modeling work using more sophistical models which are better suited to this type of situation be completed.

References

Geldon, A.L., 1989, *Groundwater Hydrology of the Central Raton Basin, Colorado and New Mexico*. U.S. Geological Survey Water Supply Paper 2288 81p.

NAH, 2008, "Comments on Approach to Stream Depletion Estimate-1-3-08". Norwest Applied Hydrology email submittal to Ms Deborah Hathaway on January 3, 2008.

S. S. Papadopulos, 2006, "Responses to Review Comments on Coalbed Methane Stream Depletion Assessment Study, February, 2006". S. S. Papadopulos & Associates, Inc. Technical Memorandum. September 27, 2006.

Discussion of Analytical Approach to Stream Depletion Estimation for the Cucharas River, Raton Basin, Colorado

The following discussion is intended as a technical critique on the use of the analytical approach to estimation of stream depletion in the draft report **Coalbed Methane Stream Depletion Assessment Study – Raton Basin, Colorado** (Papadopulos and Associates, 2007). Specifically, the discussion is restricted to the Cucharas River and the application of analytical methods to estimate stream depletion resulting from Petroglyph Operating Company's ground water pumping for coalbed methane recovery.

The following discussion pertains primarily to the use of analytical methods for estimation of the stream depletion resulting from the extraction of ground water from an adjacent aquifer. Of particular interest is the use of such methods to ascertain whether ground water in a given part of the aquifer qualifies as "nontributary" under the definition of Colorado Rules and regulations as administered by the Colorado Division of Water Resources (CDWR), State Engineer's Office (SEO). The "Water Right Determination and Administration Act of 1969" is the primary legislation that covers the distribution of water in the State of Colorado as detailed in §§37-92-101 – 602 (2003).

Definition of Nontributary Ground Water in Colorado

"Nontributary" ground water is defined in §37-90-103 as:

> *…ground water, located outside the boundaries of any designated ground water basins in existence on January 1, 1985, the withdrawal of which will not, within one hundred 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.*

Natural streams are defined in sections 37-82-101 (2) and 37-92-102 (1) (b). The rules and regulations applying to applications for well permits to withdraw ground water pursuant to Section 37-90-137(4), C.R.S. are detailed in 2 CCR 402-7 "The Statewide Nontributary Ground Water Rules". 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. 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.

The Glover-Balmer Analytical Method

In the State of Colorado, stream depletion estimates in non-designated basins are commonly performed using analytical solutions based on simplified representations of the stream-aquifer interface. The method proposed by Glover and Balmer (1954) is a well-accepted analytical solution for stream depletion associated with pumping of a well in an aquifer adjacent to a stream. In recent years, the State Engineer's Office has undertaken to evaluate stream depletion effects resulting from Coal Bed Methane (CBM) ground water extraction in the several of the major CBM basins in Colorado. The San

Juan Basin study was completed in 2006, the Raton Basin study in 2007, and the Piceance Basin study is scheduled to be completed some time in 2008. The Glover-Balmer method has been adapted for use in these evaluations. One outcome of these evaluations is a first order delineation of the area within the basins that meet the nontributary stream depletion criteria defined in §37-90-103 as described above.

The Glover-Balmer method assumes that the stream is a line source (or sink) for the aquifer (Figure 1) and is based on a series of simplifying assumptions including:

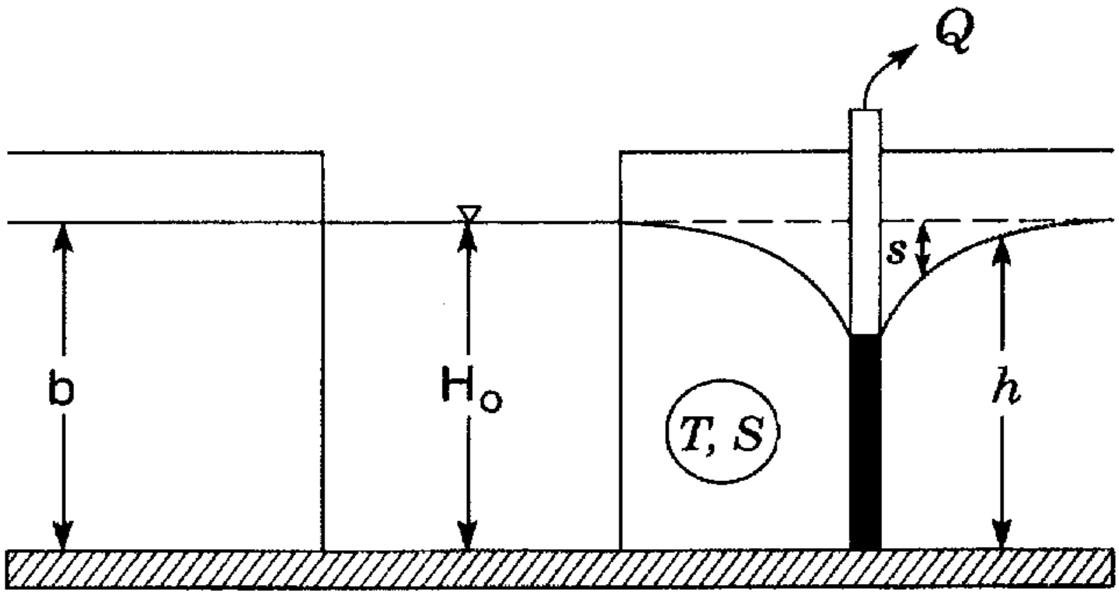
- The stream infinitely long in the horizontal plane and has low sinuosity
- The stream fully penetrates the aquifer
- The stream stage is constant and does not affect stream depletion
- There is perfect hydraulic connection between the stream and the aquifer
- The aquifer has homogeneous and isotropic properties (transmissivity and storativity) and semi-infinite lateral extent
- The stream and the aquifer are initially at hydraulic equilibrium, and the potentiometric surface in the aquifer is initially horizontal
- For unconfined aquifer conditions (the condition that the Glover-Balmer method was originally developed) , the potentiometric drawdown caused by well pumping is small compared with the saturated thickness of the aquifer so the Dupuit approximation is applicable (aquifer is horizontal and dominated by one fluid phase)
- All water pumped from the aquifer system comes solely from storage within the aquifer system and from the stream (i.e. there is not another source of water)

Simplifying Assumptions Applied to the Cucharas River in the Raton Basin Study

The Papadopulos study of the Raton Basin applied the Glover-Balmer method to determine a first order delineation of the area within the basins that meet the nontributary stream depletion criteria. It has long been recognized by hydrogeologists that the simplifying assumptions inherent in the Glover-Balmer method often bear little resemblance to reality. However, the extent to which these assumptions affect the calculated stream depletion varies significantly. The following discussion pertains to the application of the Glover-Balmer method to the Cucharas River stream depletion analysis.

Representation of the Pumped Unit as a Single Layer

The Glover-Balmer analytical solution assumes that the pumped unit only receives water from the stream (line source) or from storage within the pumped layer. In reality, the pumped unit can receive water from water bearing zones both above and below the pumped unit. The effect of not including vertical communication is to over-estimate the amount of stream depletion over time. The actual rate of flow from the overlying and underlying units to the pumped unit at any given time is dependant on the hydraulic properties and the potentiometric head differential between the pumped unit and the adjacent units.



From Butler et al, 2001

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

Where:

q	=	stream depletion rate at time ***t***
Q	=	well pumping rate
a	=	distance from the pumping well to the stream
T	=	transmissivity of the aquifer
S	=	storativity of the aquifer
Erfc	=	the complimentary error function (a probability function that returns a value between 0 and 1 for the input value)

Figure 1: Glover-Balmer Analytical Solution for Stream Depletion

Assumption of Perfect Hydraulic Connection between Stream and Adjacent Materials

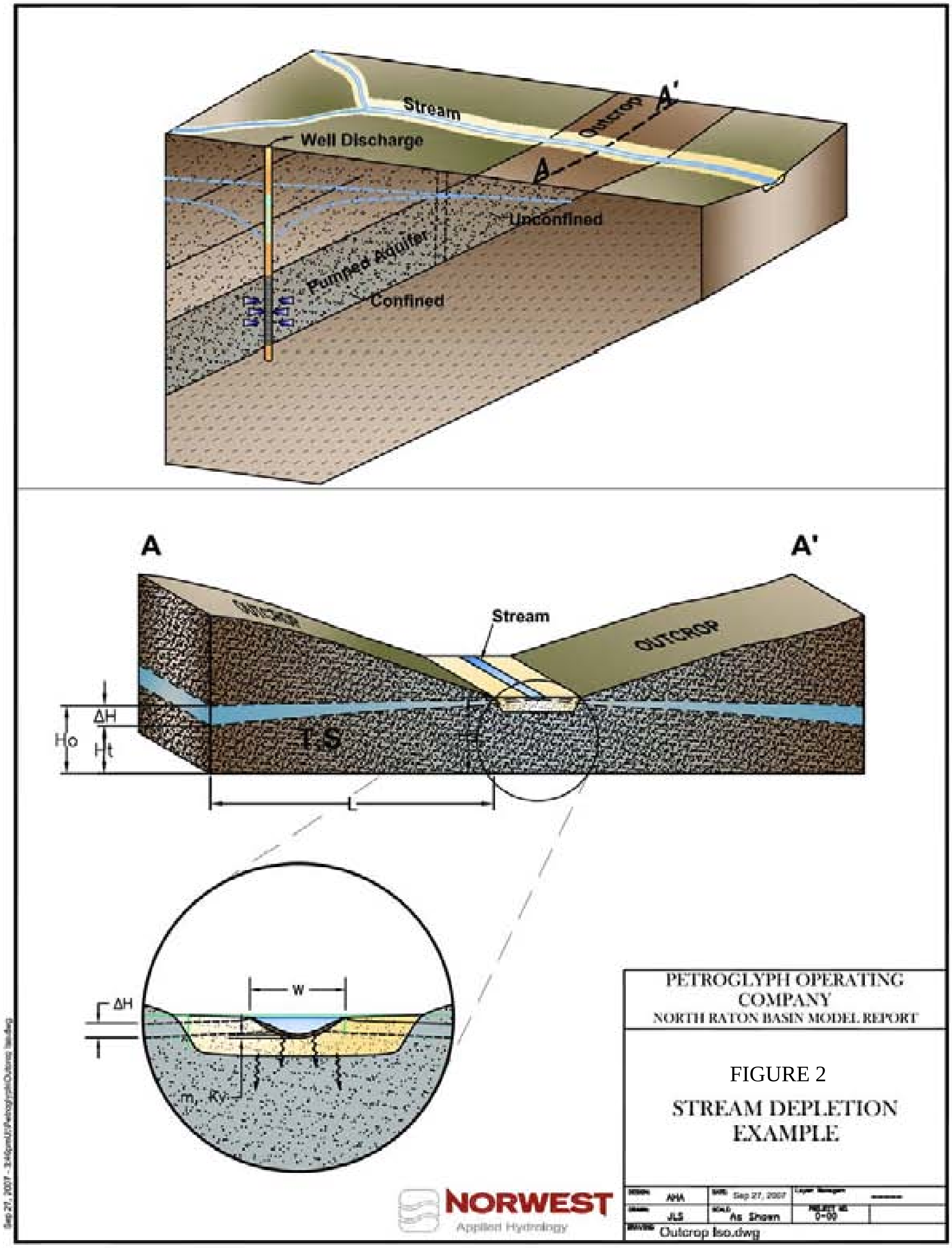
The Glover-Balmer analytical solution assumes that the stream in connection with the pumped aquifer constitutes a "line-source" and is in perfect hydraulic connection with the aquifer. Several studies have examined the impact of a number of factors on stream depletion estimates (Butler et al 2001, McCurry, 2004; Sophocleous et al., 1995). These studies found that the degree to which the stream is fully penetrating and the extent of hydraulic connection to the aquifer are the most significant factors relative to the accuracy of the estimated stream bed depletions by the Glover-Balmer method. Neglect of partial penetration and an imperfect hydraulic connection between the stream and the aquifer can result in a significant overestimation of stream depletion effects from pumping of an adjacent aquifer.

The hydraulic gradient from the stream to the alluvium is governed by the head differential between the stream and the alluvium, and the thickness of the stream material, *m* (Figure 2). Actual flow rate of water from the stream to the alluvium (per unit length of stream) is a function of the hydraulic gradient, stream bed permeability, K_v, and the width of the channel, *W* (Figure 2). Consideration of the stream bed conductance (= K_v/m) may have a significant influence on stream depletion effects even after 100 years of pumpage. A range of values for stream bed conductance that are typically used in stream depletion studies is between 10^{-6} and 10^{-4} day^{-1}. Rushton (1999) and others have noted that if potentiometric head in the alluvium or underlying materials decline to below the base of the stream bed then leakage across the stream bed will not increase with continued decline so that analytical approaches will again over-estimate stream depletion..

Representation of the Outcrop Area as a Line-Source

The Glover-Balmer analytical solution assumes that the stream in connection with the pumped aquifer constitutes a "line-source" and is in perfect hydraulic connection with the aquifer. In other words, the stream stage is assumed constant and the stream is able to supply an infinite source of water to the aquifer as pumping causes a drawdown in the aquifer potentiometric surface. The actual rate of flow from the stream to the aquifer at any given time is dependant on the aquifer properties and the potentiometric head differential between the stream and the adjacent aquifer.

The Papadopulos study of CBM pumpage and stream depletion in the Raton Basin used a modified version of the Glover-Balmer method that assumes that the outcrop area of the dipping pumped Vermejo or combined Raton-Vermejo acts as the line source. The "source" of water in the outcrop area is a combination of the water available directly in the streams crossing the outcrop and the "water-table storage" of the unconfined rocks. Unconfined storage in the outcrop area will be several orders of magnitude greater than that in the down-dip confined portion of the formation, and thus constitutes a significant "source" in the context of the basin analysis.


Stream
Well Discharge
Outcrop
A
A'
Unconfined
Pumped Aquifer
Confined
A
A'
Stream
OUTCROP
ΔH
Ho
Ht
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L
W
ΔH
m, Kv
PETROGLYPH OPERATING COMPANY
NORTH RATON BASIN MODEL REPORT
FIGURE 2
STREAM DEPLETION EXAMPLE
NORWEST
Applied Hydrology
AHA
Sep 27, 2007
JLS
As Shown
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Outcrop Iso.dwg

By structuring the problem in this manner, the calculated "depletion" is a "lumped" value that includes the outcrop storage and any natural streams that cross the outcrop area. It is acknowledged in the Papadopulos report that the computed "lumped" depletion will not precisely represent the impact on the stream and this is attributed mainly to a lagged effect between the impacts from the outcrop to the stream. This assumption requires that eventually all the depletion that is calculated for the outcrop area will manifest itself as stream depletion, albeit at a lagged time. The implication of this assumption is that any reduction in ground water storage in the outcrop area over a period of time (a decline in potentiometric head) will eventually result in an equivalent reduction in stream flow. This may be a reasonable assumption if the outcrop depletion occurs in the immediate vicinity of a stream that crosses the outcrop, but it is highly unlikely to be applicable to outcrop areas that are miles away from stream areas. Unfortunately, the ramifications of this assumed equivalency have a major effect on the delineation of nontributary areas of the aquifer since this is defined by stream depletion not by outcrop depletion.

Specific to the Petroglyph model area, the eastern outcrop of the Raton, Vermejo and Trinidad formations are crossed by the Cucharas River and Bear Creek near Walsenburg. Pre-CBM development potentiometric distributions in these units indicate a generally eastward ground water flow towards the outcrop, suggesting that ground water discharge from these units occurs in the outcrop area. Discharge of ground water may contribute to streams crossing the outcrop or may occur in the form of seeps, springs and evapo-transpiration where the water table is at or close to the ground surface. Ground water discharge may also occur to the extensive historic coal mine workings that exist along the eastern outcrop area of the Raton and Vermejo formations.

The extent to which ground water discharge contributes to the base flow of the Cucharas River and Bear Creek depends on the relative head in the outcrop area below and adjacent to the stream valleys compared to the stream stage. Potentiometric data to evaluate this relationship is sparse; however it is known that mines that had significant water inflow problems were strongly correlated with proximity to alluvium of major streams and flood plains (USGS, 1966). For example, the extensive mined area near Walsenburg lies directly below the Cucharas River alluvium and extends two miles downdip from the outcrop. This data suggests that the Raton and Vermejo Formations are locally recharged by inflow from the Cucharas River and Bear Creek alluvium where it crosses the outcrop areas of these formations (i.e. "losing" rather than a "gaining" stream reaches in this area).

Regardless of whether the Cucharas River is a gaining or losing stream as it crosses the Raton-Vermejo-Trinidad eastern outcrop area, stream depletion may occur if the water table in the outcrop area in the vicinity of the stream declines as a result of ground water extraction. Stream depletion may be a consequence of less ground water discharge to the stream from the outcrop (for a gaining stream reach) or more stream loss to the outcrop (in a losing stream reach).

Reduction in outcrop storage caused by extended CBM pumping in the deeper parts of the basin may result in relatively small (~1 ft) lowering of the water table in outcrop areas due to the high storativity of the unconfined outcrop areas compared with the storativities of deeper confined coal seams, as noted above. Close to areas where streams cross the outcrop, there may be a consequential decline in stream flow (stream depletion). However, in outcrop areas distant from natural streams, a water table decline has minimal influence on stream flows and will more likely manifest itself as reduced mine discharges or reduced flows to springs, seeps and evapo-transpiration. While these impacts are important, unless they are directly related to flows of natural streams, they should not be included in the calculation of stream depletion to determine tributary or nontributary status of the aquifer. The assumption that all outcrop depletions are accountable as actual stream depletion results in a significant over-estimation of the stream depletion effect.

The assumption that all outcrop depletion is accounted for in equivalent stream depletion can be easily examined using a simple example. Consider the cross-sectional depiction in Figure 2 that illustrates a simplified potential flow relationship between the Cucharas River and the eastern outcrop area ground water of the Raton-Vermejo-Trinidad as the river crosses the outcrop area approximately perpendicular to outcrop strike. It is assumed in this example that, prior to pumping of the down-dip units, the Cucharas is a losing stream[1] as it crosses the outcrop, that is, the stream stage is higher than the water table in the alluvium which is higher than the water table in the outcrop area.

The hydraulic gradient from the stream to the alluvium is governed by the head differential between the stream and the alluvium, and the thickness of the stream material, *m* (Figure 2). Actual flow rate of water from the stream to the alluvium (per unit length of stream) is a function of the hydraulic gradient, stream bed permeability, K_v, and the width of the channel, *W* (Figure 2). Similarly, flow rate of water from the alluvium to the bedrock outcrop is determined by head gradients and permeability, but for simplicity, assume that there is good hydraulic communication such that stream loss to the alluvium is equal to alluvial loss to the outcrop area.

Now consider the pumping in the deeper confined part of the basin that causes a depletion in the outcrop area according to the Glover-Balmer method as applied in the Papadopulos study as depicted in Figure 2. Under these assumptions, the stream eventually supplies all the water to the outcrop area to make up the depletion and maintains the water table in the outcrop area as a line source (i.e. no water table decline). In reality, in order for this to actually occur, there has to be an increase in the hydraulic gradient from the stream to the alluvium and then to the bedrock outcrop. In other words, the water table in the outcrop area up-dip from the pumping would have to decline slightly. This reality is acknowledged in the Papadopulos study and the amount of water table decline in the outcrop is estimated to be very small (~1-2 ft) even after an extended period of time due to the high storage in the outcrop area.

For purposes of this example, assume that the pumping well is located such that the outcrop point immediately up-dip from the well is at a distance *L* from the Cucharas River. If the transmissivity of the pumped unit is homogenous, the maximum decline in head (drawdown) in the outcrop area will occur immediately up-dip from the pumping

[1] Note that the example also works if the Cucharas is a gaining reach as it crosses the Raton-Vermejo-Trinidad outcrop area.

well. Assume that pumping from the well causes the water table in the up-dip outcrop area, immediately up-dip of the pumping well, to decline by a small amount Δh after an extended period of time t. The decline in head in the Cucharas River alluvium and in the outcrop area in the immediate vicinity of the River resulting from the pumping will be somewhat lower than Δh. However, for purposes of conservatism, assume that the maximum drawdown occurs uniformly along the outcrop and also in the alluvium. So, if the stream water level is fixed, the potentiometric head difference between the stream and the alluvium increases by the amount Δh over the time t.

Assuming steady state flow, the change in hydraulic gradient causes a change in flow rate from the stream (i.e. stream depletion, Δq) per unit stream length (=unit width of outcrop) by the end of time t given approximately by:

$$\Delta q = \Delta h * W * K_v/m \quad \text{(per unit width of outcrop)}$$

Where:

Δq = stream depletion rate per unit length of stream reach at end of time t
Δh = change in head difference between stream and alluvium over time t
W = width of the channel,
K_v = vertical permeability of the stream bed materials.
m = thickness of the stream bed materials

Over the same period of time, t, the average rate of change in storage within the outcrop (i.e. outcrop depletion, ΔS) per unit width of outcrop, is approximately given by:

$$\Delta S = S_y * L * \Delta h / t \quad \text{(per unit width of outcrop)}$$

Where:

ΔS = outcrop depletion rate per unit width of outcrop at end of time t
S_y = specific yield of unconfined outcrop materials
L = length of outcrop contributing to stream depletion calculation
Δh = change in head in outcrop materials over time t

For a unit outcrop width, the ratio of the average change in rate of flow from the stream (stream depletion, Δq) to the average rate of change of storage (outcrop depletion, ΔS) yields the following relationship:

$$\frac{\Delta q}{\Delta S} = \frac{\Delta h * W * K_v/m}{S_y * L * \Delta h / t} = \frac{W * K_v * t}{S_y * L * m}$$

Note that the term Δh drops out of the ratio equation so that the calculated stream to outcrop depletion ratio is independent of the assumed drawdown due to pumping. For the Cucharas River example, the width of the river channel is approximately 20 feet. The specific yield of the outcrop materials is likely to range between 0.05 to 0.2, with a tendency to the higher value in light of the fact that much of the outcrop areas of the Vermejo and Raton in this area has been mined. The time frame of interest for tributary/nontributary determination of stream depletion is 100 years (~36,500 days). The length of outcrop area that could be influenced from the pumping at Petroglyph CBM producing wells is about 6 miles (~30,000 ft). For stream depletion analyses, where direct measurements of stream bed materials are not available, the streambed conductance, K_v/m is usually assumed to be in the order of 10^{-5} day^{-1} with a range of 10^{-4} to 10^{-6} day^{-1} (Brian Aherns, pers. comm.).

Using the above values, the stream to outcrop depletion ratio can be calculated for various values for K_v/m and S_y, as shown graphically in Figure 3. It can be seen that the ratio varies significantly (note the log scale) depending on the stream bed conductance and the specific yield of the outcrop. For the range of stream bed conductances used in these calculations, the ratio approaches 5% for relatively high stream bed conductance and low specific yield. For the 10^{-5} day^{-1} value of stream bed conductance typically used for stream depletion analyses, the calculated stream depletion varies from 0.12% to 0.5% of the outcrop depletion for outcrop specific yields ranging between 0.05 and 0.2.

For the Cucharas River example, the use of the Glover analysis for outcrop depletion and equating this to stream depletion results in over estimating the stream depletion by between 200 to 800 times. If the Glover method is applied to calculate outcrop depletion, then consideration should be given to the extent that stream bed conductance and outcrop length influences the equivalent stream conductance, and appropriate adjustments made. The importance of this consideration with respect to tributary/nontributary determination is illustrated for the Cucaras River example in Figure 4. In this figure, the "unadjusted" curve shows the results of applying the Glover analysis to the outcrop and assuming equivalency between calculated outcrop depletion and stream depletion. For this analysis, a transmissivity of 230 ft^2/d and a confined storativity of 2 x 10^{-3} was assumed for the pumped interval. These values are used in the Papadopulos Raton Basin study for the Cucharas watershed.

The unadjusted curve on Figure 4 shows that Glover predicts that the stream depletion, after 100 years of pumping, declines from 100% to 25% of the pumping rate as the downdip distance of the well from the outcrop increases from 0 to 20 miles. The nontributary stream depletion criterion of <0.1% of the pumping rate is clearly not approached within this 20 mile range from the outcrop when the Glover method is applied in this manner.

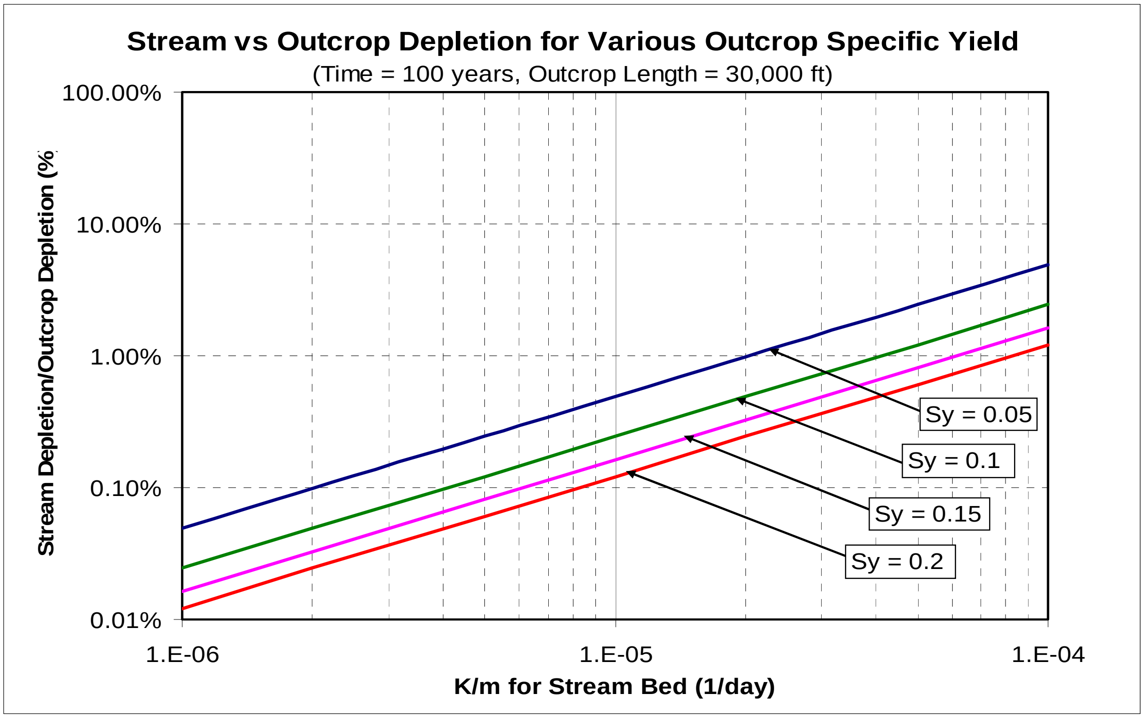

Figure 3: Stream to Outcrop Depletion Ratio vs Outcrop Specific Yield

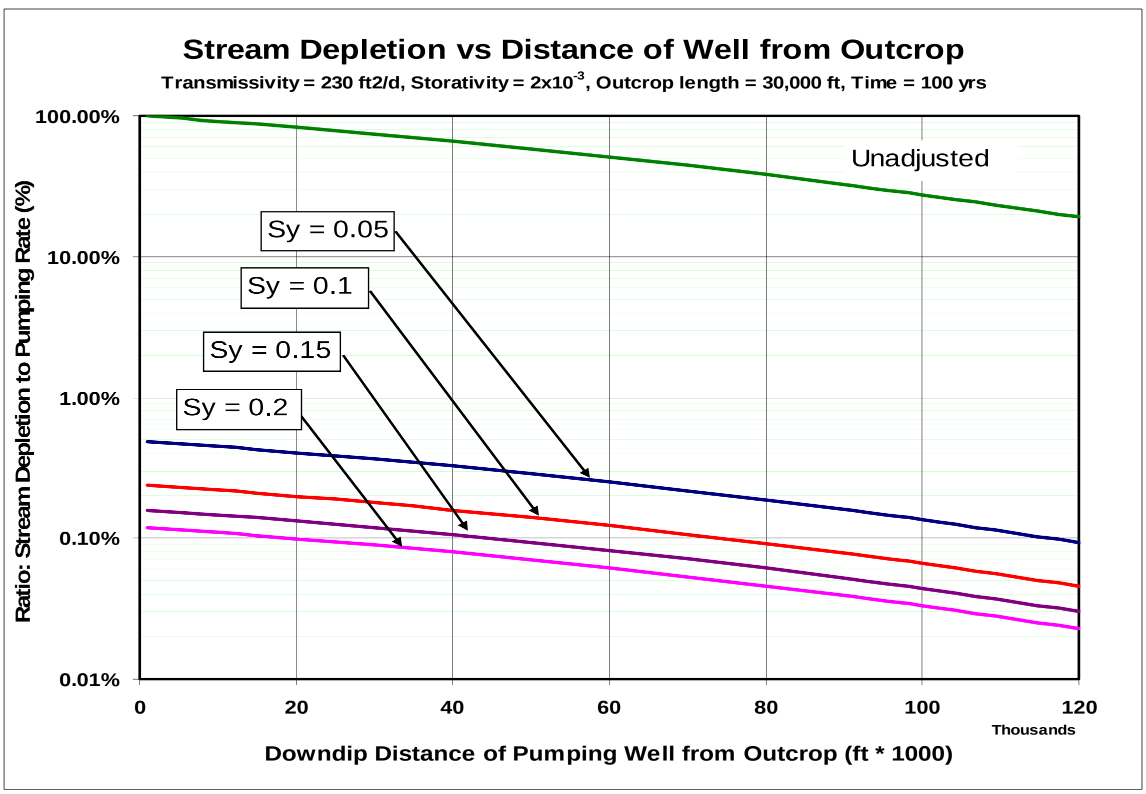

Figure 4: Stream Depletion vs Downdip Distance of Well from Outcrop

However, if the adjustment factors for stream depletion in the Cucharas River example are applied to the outcrop depletion calculations, a very different picture emerges. For this example, adjustment factors for stream conductance (K/m) corresponding to outcrop specific yields ranging from 0.05 to 0.2 (Figure 3) were applied to the Glover calculations. The adjusted Glover stream depletion values, as a function of distance from the outcrop, are shown in Figure 4. It can be seen that the nontributary stream depletion criterion of <0.1% of the pumping rate after 100 years is met at various distances from the outcrop, ranging from about 4 to 22 miles depending on the outcrop specific yield.

Difference between Analytical and Numerical Simulations of Petroglyph Pumping

Numerical simulation of CBM pumping at the Petroglyph Operations can include many conditions that analytical solutions such as Glover-Balmer cannot take into account. It is not surprising that numerical solutions may yields very different results with respect to stream depletion effects compared with analytical solutions. This is because the Glover analytical solution over-estimates the stream depletion effect, particularly when applied in the manner used by the Papadopulos study, as described above. The over-estimations can be very significant depending on the stream bed conductance values assumed.

Numerical modeling of the Cucharas River depletion effects due to pumping at Petroglyph operations indicate that, after 100 years of pumping, stream depletion effects in the outcrop area of the pumped units do not exceed the 0.1% of pumpage criterion for nontributary designation. There are several reasons that these results differ from the Glover analytical solution results for the Cucharas River as reported in the Papadopulos study. In all cases, the Glover analytical solution over-estimates the stream depletion effects for the Cucharas River compared with the numerical solution. While some conservativeness is appropriate in performing stream depletion analyses, the accumulation of over-estimates of depletion effects may be several orders of magnitude. This clearly influences the potential for designation of nontributary ground water which is defined to a very tight stream depletion criterion.

The main differences between the numerical model constructed for the Petroglyph Operations in the Raton Basin and the Glover-Balmer analytical solution as applied in the Papadopulos study are as follows:

1) Contribution from Water-Bearing Units above and below Pumped Unit

   The numerical model is a multi-layer model that allows contribution of flow to the pumped Vermejo and Raton Formations from the overlying Poison Canyon and Cucharas units and the underlying Trinidad Sandstone. Operational data from Petroglyph clearly show very good vertical communication between the Vermejo and the Trinidad sandstone. Contributions from above and below reduce the stream depletion effect as compared with analytical solutions that assume that the pumped unit only receives water from the stream (line source) or from storage within the pumped layer.

2) Inclusion of Stream Bed Conductance

The numerical model includes consideration of the stream bed conductance for the Cucharas River that has a significant influence on stream depletion effects even after 100 years of pumpage. A range of values for stream bed conductance (K/m) that are typically used in stream depletion studies were employed. The Glover-Balmer analytical solution assumes that the stream in connection with the pumped aquifer constitutes a “line-source” and is in perfect hydraulic connection with the aquifer. The assumption of perfect connection leads to stream depletion over-estimation, particularly when the analytical solution is applied to the outcrop rather than the stream, as noted below

3) Representation of the Outcrop Area as a Line-Source

The Papadopulos study of CBM pumpage and stream depletion in the Raton Basin used a modified version of the Glover-Balmer method that assumes that the outcrop area of the dipping pumped Vermejo or combined Raton-Vermejo acts as the line source. The “source” of water in the outcrop area is a combination of the water available directly in the streams crossing the outcrop and the “water-table storage” of the unconfined rocks. By structuring the problem in this manner, the calculated “depletion” is a “lumped” value that includes the outcrop storage and any natural streams that cross the outcrop area. As described in detail above, the use of Glover-Balmer to estimate outcrop depletion is not inappropriate, but the assumption that this can be equated with stream depletion can lead to over-estimations of stream depletion of two to three orders of magnitude. The numerical model can account for the unconfined conditions in the outcrop area and more accurately portray the relationship between outcrop depletion to stream depletion.

References

Butler, J.J., V.A. Zlotnik, M. Tsou. 2001. Drawdown and Stream Depletion Produced by pumping in the Vicinity of a Partially Penetrating Stream. *Ground Water* 39(5), 651-659.

Glover, R. E. and C. G. Balmer, 1954. River depletion resulting from pumping a well near a river. *Am. Geo-phys. Union Trans*. 35(3), 468-470.

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

Sophocleous, M.A., A. Koussis, J.L. Martin, S.P. Perkins, 1995, Evaluation of simplified stream-aquifer depletion models for water rights administration, *Ground Water*, 33(4), 579-588.

S.S. Papadopulos and Associates, Inc., 2007, Coalbed Methane Stream Depletion Assessment Study – Raton Basin, Colorado.

Zlotnik, V.A., H. Huang and J. J. Butler, 1999. Evaluation of Stream Depletion Considering Finite Stream Width, Shallow Penetration, and Properties of Streambed Sediments. In *Proceedings of Water 99*, *Joint Congress*, 221-226. Brisbane, Australia: (also available at: http://www.kgs.ku.edu/StreamAq/Reports/99/zlotnik.html

Evaluation of the analytical approach to calculate stream depletion

Analytical methods rely on simplifying assumptions that may or may not be valid for a particular site. The validity of the analytical solution is determined by the degree to which the assumptions are valid. The Glover-Balmer method (1954) has been used in the Papadopulos study to calculate depletion of the Cucharas River due to pumping of the Petroglyph CBM wells. In the Appendix of the Report, several assumptions of the Glover-Balmer method are shown to be inappropriate for the Petroglyph site. In my assessment, the most critical assumption of the Glover-Balmer method is that the stream is fully-penetrating. When an aquifer is pumped, water is removed from storage in the aquifer, leading to drawdown which is often represented as a cone of depression around the well. Initially, the water is removed from the region of the aquifer near the pumping well, so the cone of depression remains near the pumping well. As pumping continues, more water is removed from more distant regions of the aquifer, and the cone of depression expands to encompass a larger region of the aquifer. The cone of depression will continue to grow unless an external source of water is encountered. A surface water body, such as a stream, is one example of an external source of water. If a stream is fully-penetrating, the stream is essentially a boundary of the aquifer. The cone of depression cannot extend beyond the stream, and therefore no water can be removed from storage in the aquifer beyond the stream. Thus, the stream becomes a significant source of water. If a stream is partially-penetrating, some pumped water will be drawn from the stream, but water will also be removed from storage in the region of the aquifer that lies beyond the stream, since the cone of depression can extend beyond the stream. The assumptions of a fully-penetrating stream can severely overestimate the amount of water taken from the stream. This conclusion is supported by theoretical and numerical studies (Zlotnik et al., 1999; McCurry, 2004), and by modeling studies of the Middle Rio Grande Basin in New Mexico. A groundwater flow model of the Middle Rio Grande basin showed that seepage from the Rio Grande as a result of pumping was much less than the seepage the was predicted using the Glover-Balmer method (Bartolino and Cole, 2002).

With base flow of approximately 6 ft^3/s in the Cucharas River, stream depth is estimated from Manning's equation to be on the order of 1-2 ft. This calculation is based on assumptions of uniform flow, a five-foot wide rectangular channel, natural stream bed (Manning's n of 0.06), and a channel bottom slope of 0.004 ft/ft. These values are taken to be representative of the site conditions or conservative estimates. If the aquifer is greater than 1-2 ft thick in the outcrop area, the Cucharas River is not fully-penetrating and thus the stream depletion would be over-estimated using the Glover-Balmer method.

In Section 6.1.2 of the Papadopulos report, arguments are presented to justify the assumptions of the Glover-Balmer method. One argument they present in support of the fully-penetrating stream assumption is that ". . . partial penetration of a well is not important when considering impacts at a distance of more than 1.5 times the aquifer thickness." This is a valid statement, but it does not support the assumption of a fully-penetrating stream. Basic well hydraulics theories assume that the pumping well is fully-penetrating, thus flow is horizontal throughout the aquifer. If a well is partially-penetrating, vertical gradients exist near the well, and the drawdown predicted by standard semi-analytical solutions, such as the solution of Theis (1935), are not valid. At a distance from the pumping well of 1.5 times the aquifer thickness, vertical gradients are negligible; thus the assumption of horizontal flow is valid, and drawdown can be computed by standard semi-analytical solutions.

The basis of this argument is that flow due to pumping is essentially horizontal in an aquifer beyond a distance of 1.5B from the well (B is the aquifer thickness). With this argument, horizontal flow exists near a partially-penetrating stream, so water must be drawn from both the stream and the aquifer beyond the stream, as shown in Figure 1. If water is drawn from beyond the stream, stream depletion is lower for a partially-penetrating stream than for a fully-penetrating stream.

From: Tom Dea [tdea@tza4water.com]
Sent: Wednesday, January 02, 2008 6:18 PM
To: Debbie Hathaway
Cc: B.F. Hill; Bob Krassa
Subject: Coalbed Methane Stream Depletion Assessment Study - Raton Basin

Attachments: Hill04-3.pdf
Debbie,

We have reviewed the draft report dated November 2007 and we are providing the following comments and additional information for your consideration.

Attached please find a letter report we prepared for Hill Ranch dated September 10, 2004. We believe the information included in our letter report provides evidence that the groundwater in the coal seams in the area south of the Purgatory River (underlying the Hill Ranch) should be classified as non-tributary. We further believe that the known geologic structures in the area (dikes, sills, etc...) do not lend themselves to application of the Glover technique. Several sources, including the October 2002 report contained in your draft prepared by Glen Graham and Dick Wolfe of the Colorado Division of Water Resources, state that the geologic structure of the coal seams is layered and interbedded and that there are significant barriers to the vertical and horizontal movement of water.

The lenticular, bedded nature of the coal seams is not a depositional environment that lends itself to accurate evaluation with the Glover technique. However, if use of the Glover technique is applied with the following parameters of coal:

Transmissivity = 69.26 gpd/ft [Mean Transmissivity for Coal and Carbonaceous Shale (Hydrology of Area 61 – USGS Open File Report 83-132)]
Specific Yield = 2.75% [Average Specific Yield for Shale (Johnson Groundwater & Wells)

TZA has run several iterations using the Glover analysis in the IDS AWAS program (Version 1.5.0) to determine at what distance from the outcrop of the Vermejo coals that the formation water contained in the Vermejo coals would likely be considered nontributary.

Utilizing a pumping period of 100 years and a distance of 2.6 miles between the pumping well and the Raton / Vermejo contact, the calculated cumulative volume of depletion was 0.10% of the total pumped volume. Wells placed at a distance of greater than 2.6 miles from the point where the formation outcrops would therefore have a net impact of less that 0.1% after a cumulative pumping period of 100 years. Using these parameters, wells greater than 2.6 miles from the outcrop should therefore be nontributary as defined by the SEO. A circle of 2.6 mile radius could be drawn at the Raton Vermejo outcrop where it crosses the Purgatory River. Using this methodology, all Vermejo coal seam water should be classified as nontributary underlying the Hill Ranch property.

Based on these results, all wells producing water from the Vermejo coal seams that are located greater than 2.6 miles from the location where the Raton/Vermejo contact intersects the Purgatory River should be able to obtain a groundwater classification as nontributary.

We believe that both the Glover analysis and groundwater models similar to the ones used for the Basin Resources case are not accurate due to the complex geology of the area. Available water level information indicates that there is not a continuous gradient from point of recharge to point of discharge throughout the coal seams. Without a continuous gradient, water will not move from point of recharge to point of discharge.

We do agree that additional pressure data (water levels) would be beneficial. However, detailed long term data is not likely to be attainable due to the proprietary nature of the Oil and Gas industry. Based on our limited research, we believe additional water level information should be reviewed from oil and gas geophysical logs throughout the entire basin. We believe that additional information available from oil and gas logs will show that water levels in the coal seams throughout the basin do not show a continuous groundwater gradient, but instead will show that groundwater is compartmentalized throughout the Raton Basin. Dr. Anthony Gorody's report includes water quality information from coal seams and the water quality information indicates that the water is compartmentalized.

While we have had a limited time to review the draft study results, we do not feel that the use of the Glover technique with the broad aquifer parameters described in the draft report, is adequate to develop an accurate picture of the coal seam hydrogeology of the Raton Basin, or to use as a tool for very important water rights administration issues throughout the Raton Basin.

If you have any questions regarding this e-mail please call me. I look forward to meeting you on January 4, 2008

Sincerely,

Tom Dea

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September 10, 2004

Robert F.T. Krassa, Esq.
Krassa & Miller, LLC
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Boulder, CO 80301

Re: Hill Ranch Groundwater Classification

Dear Bob:

This letter report has been prepared to provide geologic and hydrogeologic information that was used to evaluate the tributary / nontributary status of the groundwater in the coal seams of the Raton and Vermejo formation underlying Hill Ranch property located in southern Colorado.

According to the Colorado Revised Statutes section 37-90-103(10.5) nontributary ground water has the following definition. "*Nontributary ground water* means that ground water, located outside the boundaries of any designated ground water basin in existence on January 1, 1985, the withdrawal of which will not, within one hundred years, deplete the flow of a natural stream, including a natural stream as defined in sections 37-82-101 (2) and 37-92-102 (1) (b), at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal…."

Background

We began by reviewing two United States Geologic Survey (USGS) reports titled "Hydrology of Area 61, Northern Great Plains and Rocky Mountain Coal Provinces, Colorado and New Mexico, Open File Report 83-132" and "Ground Water Hydrology of the Central Raton Basin, Colorado and New Mexico, Water Supply Paper 2288". These reports were relied upon to determine general geologic and aquifer properties for the area underlying Hill Ranch. Both of these publications were completed before extensive drilling and development of coal bed methane (CBM) resources took place in the area.

Geologic Information

Additional information about the structural geology of the area was obtained by reviewing geophysical logs from the Colorado Oil and Gas Conservation Commission's (COGCC) website. A map showing the Hill Ranch general location and locations of cross section wells is included as Exhibit A. We reviewed geophysical logs in the area and then developed an east-west cross section through the Hill Ranch property in the southern portion of the Raton Basin. The east-west cross section is included as Exhibit B. Data plotted on the cross section includes the following:

- Ground surface elevations
- Top of Raton formation (where not at surface)
- Base of Raton formation / top of Vermejo formation
- Base of Vermejo formation / top of Trinidad formation

- Base of Trinidad formation (or bottom of completed well)
- Perforated intervals of completed wells (top and bottom only)
- Static water levels (where available)
- Approximate contact of the Raton / Vermejo outcrop with the Purgatoire River
- Approximate outcrop of the Trinidad / Pierre outcrop with the Purgatoire River

After preparation of the east-west cross section, we attempted to use existing geophysical logs to develop a detailed stratigraphic cross section. Development of a detailed stratigraphic cross section was not feasible because the subsurface geology is very complicated and the coal seams are not laterally continuous in the area of investigation. The high degree of geologic variability made correlation of the Vermejo and Raton coal seams impractical at distances greater than one mile. Our attempt to correlate geophysical logs confirmed the complex nature of the subsurface geology and the existence of faults and dikes throughout the study area.

The geophysical information available points to a lack of homogeneous, isotropic formation material in the Raton and Vermejo formations underlying the Hill Ranch property and throughout the study area. After reviewing geologic information we ruled out the application of stream depletion analysis using groundwater flow models or the Glover analysis technique, since these methods rely on the application of isotropic, homogeneous aquifer properties to compute results.

<u>Hydrology of the Raton, Vermejo, and Trinidad Formations</u>

Static water level data were collected from available geophysical logs and it shows that no continuous hydraulic gradient exists in the study area. A continuous gradient would indicate groundwater flow from west to east through the Raton and Vermejo formations. We anticipated finding a continuous and relatively uniform gradient from west to east as previously reported in “Hydrology of Area 61, Northern Great Plains and Rocky Mountain Coal Provinces, Colorado and New Mexico, Open File Report 83-132” and “Ground Water Hydrology of the Central Raton Basin, Colorado and New Mexico, Water Supply Paper 2288.” The static water levels measured during well construction activities provides evidence that the groundwater in the coal seams is compartmentalized and that neither vertical nor horizontal flow takes place through the Raton or Vermejo formations over large distances.

We interviewed employees of Evergreen Resources during the course of our investigation. Evergreen Resources has constructed many coal bed methane (CBM) wells on the Hill Ranch and surrounding areas. Staff members at Evergreen Resources stated that the Raton and Vermejo formations are often dry during drilling activities and that water production is often not encountered until the Trinidad formation is penetrated. The fact that many CBM wells are dry during construction is further evidence that groundwater within the Raton and Vermejo formations is compartmentalized.

East-West Cross Section

As shown on the east-west cross section in Exhibit B, 8 of the 14 wells that contained water level records had static levels below 6,080 feet above mean sea level (MSL), which is the elevation at the location where the Purgatoire River flows across the outcrop of the base of the Trinidad formation. COGCC maps do not indicate the elevation of the Vermejo / Trinidad contact, however, the COGCC maps indicate the Raton / Vermejo contact is at an approximate elevation of 6,260 feet above MSL.

Geophysical logs indicated that four of the six wells with water levels measured above 6,260 feet MSL are at the western edge of the cross section, near the South Fork of the Purgatoire River. The two remaining wells with water levels measured above the Raton / Vermejo contact with the Purgatoire River are located near the center of the study area. The remaining 12 wells all have water levels below the contact elevation of the Raton / Vermejo with the Purgatoire River. This inconsistency indicates that water levels cannot be correlated across large distances within the study area.

Without a hydraulic gradient from point of recharge to point of discharge, groundwater in the coal seams will only flow in the down gradient direction. Water will not flow uphill. Water level measurements in the east-west cross section show that no gradient exists that would create lateral movement of groundwater through the coal seams from the point of recharge to the point of discharge underlying the study area. Water level measurements also indicate that there is no hydraulic connection between surface water in the Purgatoire River (including the associated alluvial aquifer) and groundwater that is contained in the coal seams. Water levels in the coal seams are below water levels in the Purgatoire River system. This information points to the lack of groundwater movement in the vertical direction. Water level measurements from the east-west cross section show that hydraulic barriers such as dikes, sills and structural traps compartmentalize the water in the coal seams. Variable water level measurements throughout the study area are further proof that hydraulic barriers exist and that the presence of such barriers limits groundwater movement both vertically and laterally.

While we believe the geologic cross section information from the east-west section combined with water level information proves that the groundwater in the Raton and Vermejo coal seams is nontributary, staff members from the SEO requested additional water level information be evaluated on a north-south cross section in the eastern portion of the Raton Basin.

North-South Cross Section

We reviewed additional information available from the COGCC and we located several wells in a north-south projection that contained geologic and water level records from the logging operations. The water level measurements from the north-south cross section do not indicate a clear direction of groundwater movement in the study area. The north-south cross section is included as Exhibit C.

Aquifer and Coal Seam Interactions

Additional information that was considered included water quality data and results from the "COGCC-Sponsored Baseline Environmental Data Survey" prepared by Anthony W. Gorody. This information was recently published and results of this study indicate that lateral and vertical communication between aquifers and coal seams are poor. Dr. Gorody has reported that water quality from shallow groundwater sources is significantly different when compared to that of groundwater produced from the Raton and Vermejo coal seams. Dr. Gorody concluded that it was not possible to correlate produced water patterns beyond a region with a ¾ mile radius. Dr Gorody also found that the fluid pressure gradients in the coal seams are below hydrostatic gradients of the aquifers in many areas throughout the Raton Basin. Dr. Gorody's finding that water pressures in the coal seams is below hydrostatic gradients is further evidence that the coal seams have poor vertical and lateral communication throughout the study area. Dr. Gorody's report provides additional evidence that no vertical or lateral movement of groundwater exists in the coal seams of the Raton or Vermejo formations. Dr. Gorody's report is included as Exhibit D – CD Rom Disc.

Water Age Dating

One final piece of information evaluated as part of our study was age dating of water in the Vermejo coal seams. Age dating was been performed by Mr. Paul Oldaker for Cedar Ridge, LLC. The location of the study was northwest of Aguilar, Colorado. Mr. Oldaker found that the water in the Vermejo coal seams was at least 1,000,000 years old and could be much older. Mr. Oldaker found that surface samples and CBM samples came from separate and different sources and that the CBM reservoir was not currently being recharged from the surface. The age of the groundwater in the Vermejo coal seams is further evidence of flow boundaries that inhibit groundwater flow. A copy of this report is included in Exhibit E.

<u>Summary / Conclusions</u>

TZA obtained drilling and completion information available from the COGCC for a number of wells in and around Hill Ranch property. We have reviewed publicly available geologic and hydrogeologic reports along with additional water quality reports and water age dating information for the Raton Basin area.

The water level data for both east-west and north-south cross sections shows that the water table elevation is highly variable within the Raton Basin throughout the study area. Water levels were evaluated and an attempt was made to correlate the geophysical logs for individual coal seams in both the Raton and Vermejo formations. The high degree of variability in water levels recorded during electric logging confirm the highly variable stratigraphy of the area and indicate that geologic structures exist within the Raton and Vermejo formations that create boundaries to groundwater movement.

The fact that the water levels in the coal seams is hydraulically lower than that of the surface water combined with the lack of water flowing from the surface into the coal seams is evidence that the surface water is not hydraulically connected to the water within the coal seams. Based on this evidence it is TZA's determination that the water located in the coal seams beneath the Hill Ranch property is in fact nontributary.

If you have any questions regarding this letter report or the attached information please call me at 303-971-0030.

Sincerely,

Tom Dea

Thomas M. Dea, P.E.

cc: Bobby Hill

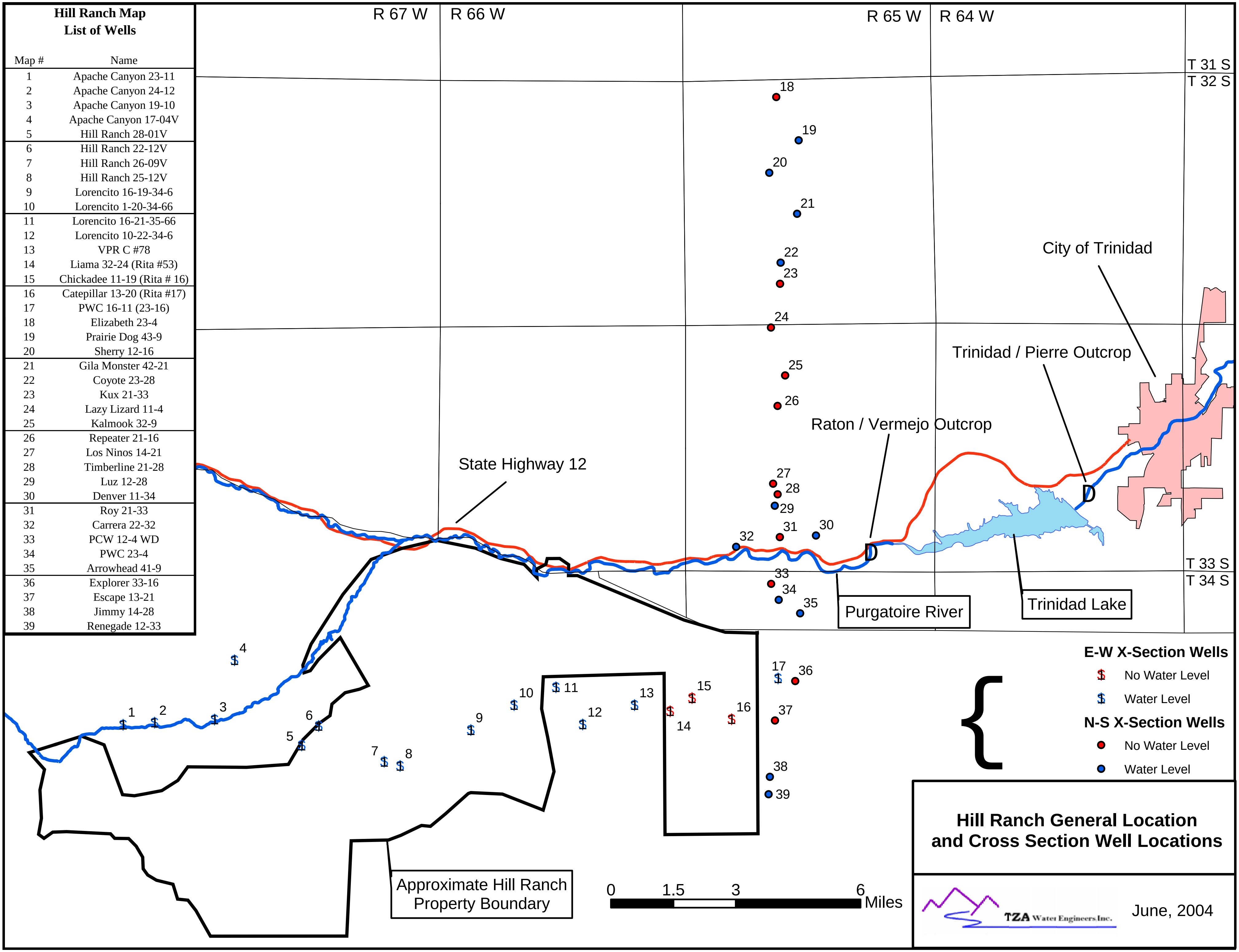
attachments

Hill04-3.doc

Hill Ranch Groundwater Classification

Exhibit A

General Location Map and Cross Section Well Locations



Hill Ranch Map
List of Wells

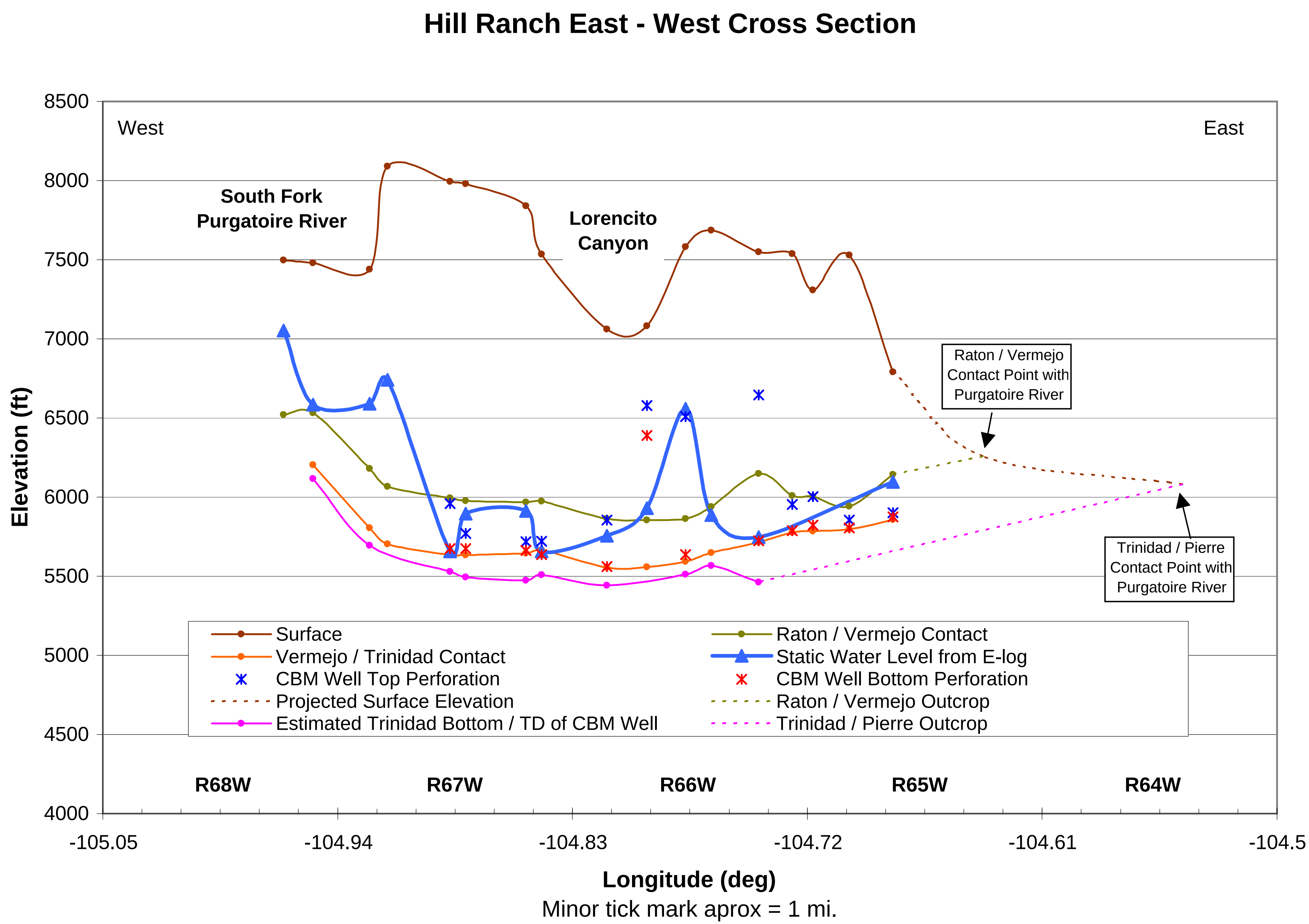
Map #	Name
1	Apache Canyon 23-11
2	Apache Canyon 24-12
3	Apache Canyon 19-10
4	Apache Canyon 17-04V
5	Hill Ranch 28-01V
6	Hill Ranch 22-12V
7	Hill Ranch 26-09V
8	Hill Ranch 25-12V
9	Lorencito 16-19-34-6
10	Lorencito 1-20-34-66
11	Lorencito 16-21-35-66
12	Lorencito 10-22-34-6
13	VPR C #78
14	Liama 32-24 (Rita #53)
15	Chickadee 11-19 (Rita # 16)
16	Catepillar 13-20 (Rita #17)
17	PWC 16-11 (23-16)
18	Elizabeth 23-4
19	Prairie Dog 43-9
20	Sherry 12-16
21	Gila Monster 42-21
22	Coyote 23-28
23	Kux 21-33
24	Lazy Lizard 11-4
25	Kalmook 32-9
26	Repeater 21-16
27	Los Ninos 14-21
28	Timberline 21-28
29	Luz 12-28
30	Denver 11-34
31	Roy 21-33
32	Carrera 22-32
33	PCW 12-4 WD
34	PWC 23-4
35	Arrowhead 41-9
36	Explorer 33-16
37	Escape 13-21
38	Jimmy 14-28
39	Renegade 12-33

Hill Ranch General Location and Cross Section Well Locations

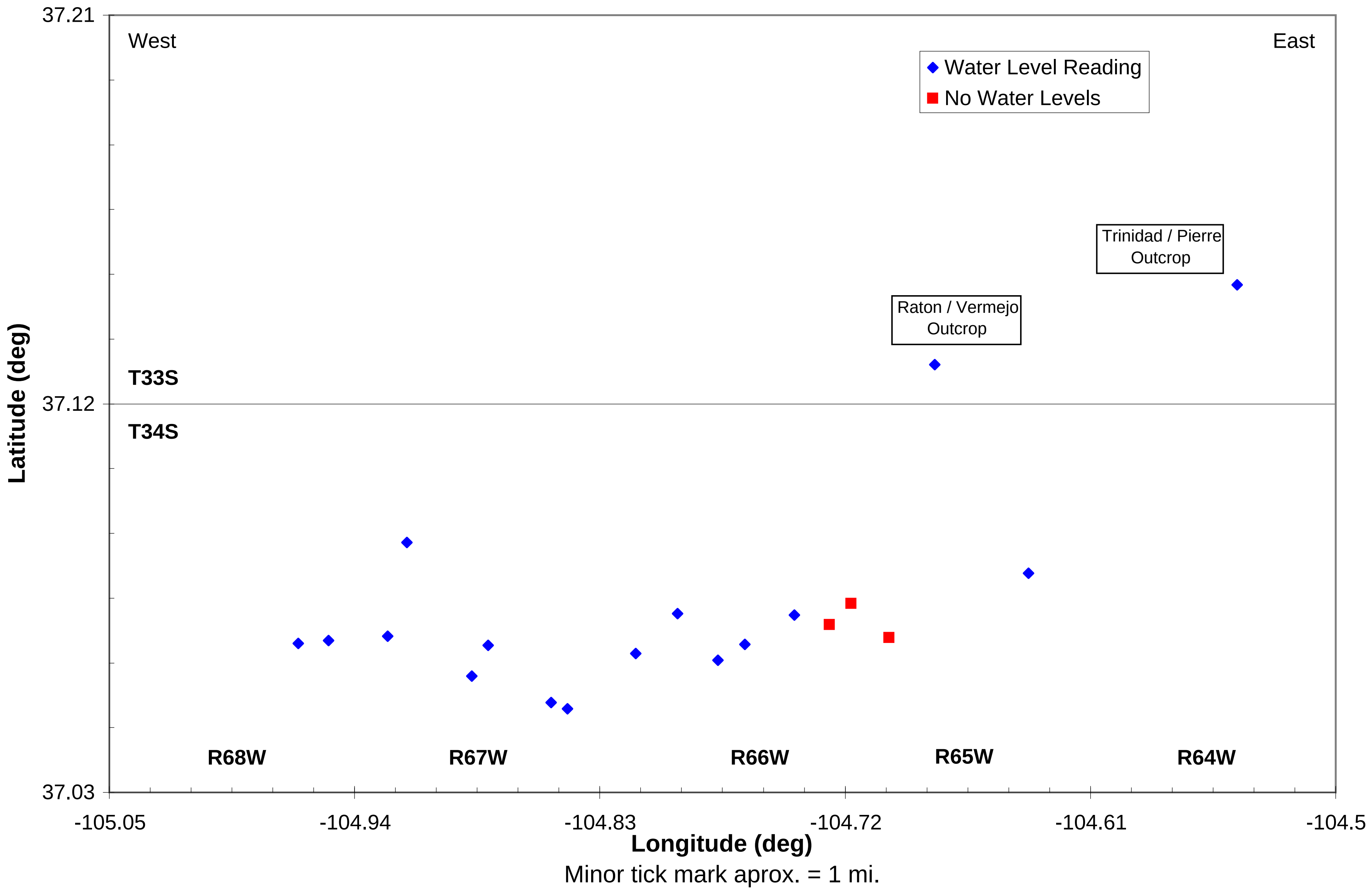
Hill Ranch Groundwater Classification

Exhibit B

East-West Cross Section


Hill Ranch East - West Cross Section
West
East
South Fork
Purgatoire River
Lorencito
Canyon
Raton / Vermejo
Contact Point with
Purgatoire River
Trinidad / Pierre
Contact Point with
Purgatoire River
Elevation (ft)
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
Surface
Raton / Vermejo Contact
Vermejo / Trinidad Contact
Static Water Level from E-log
CBM Well Top Perforation
CBM Well Bottom Perforation
Projected Surface Elevation
Raton / Vermejo Outcrop
Estimated Trinidad Bottom / TD of CBM Well
Trinidad / Pierre Outcrop
R68W
R67W
R66W
R65W
R64W
-105.05
-104.94
-104.83
-104.72
-104.61
-104.5
Longitude (deg)
Minor tick mark aprox = 1 mi.

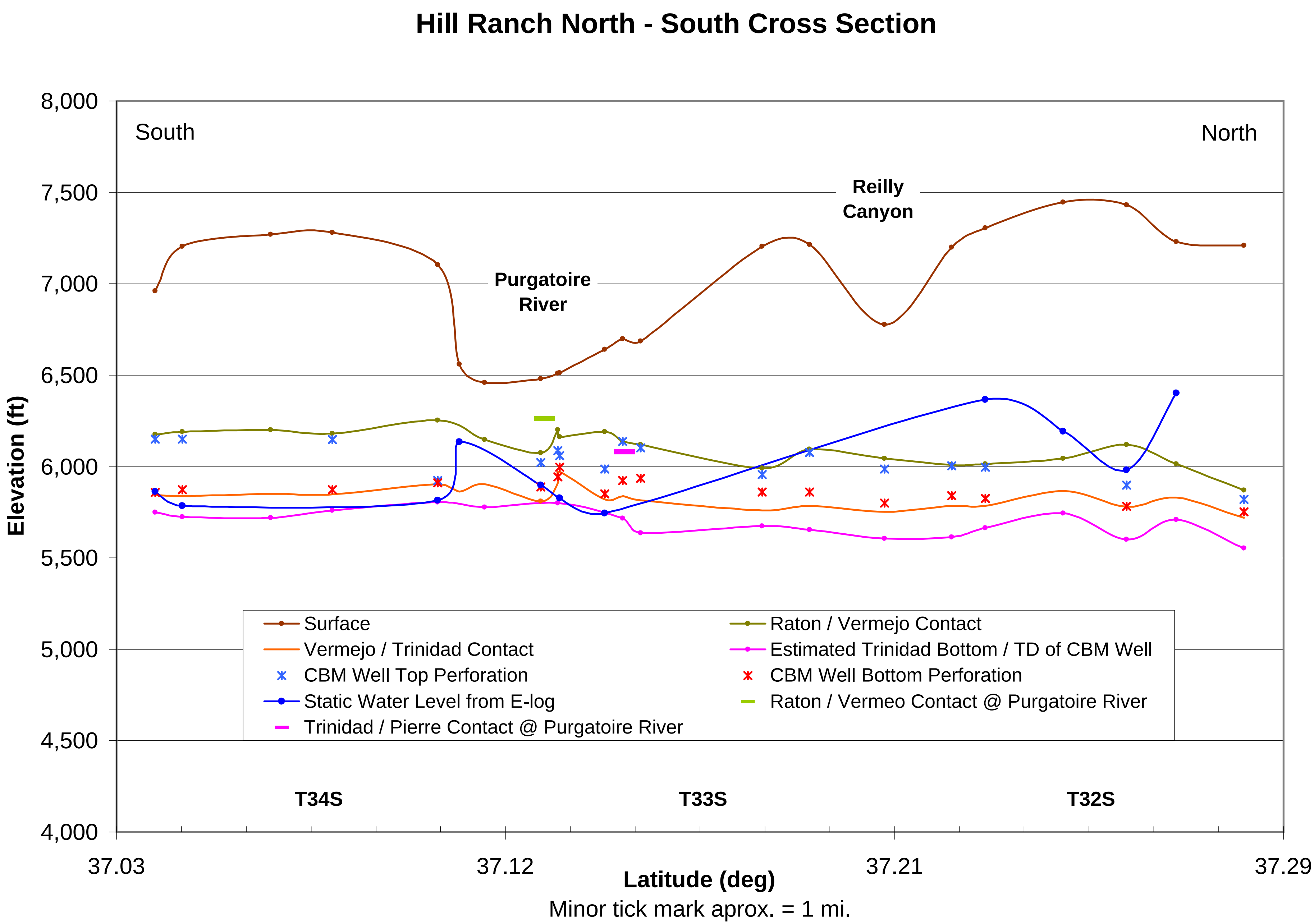
Hill Ranch
Well Locations East - West Cross Section



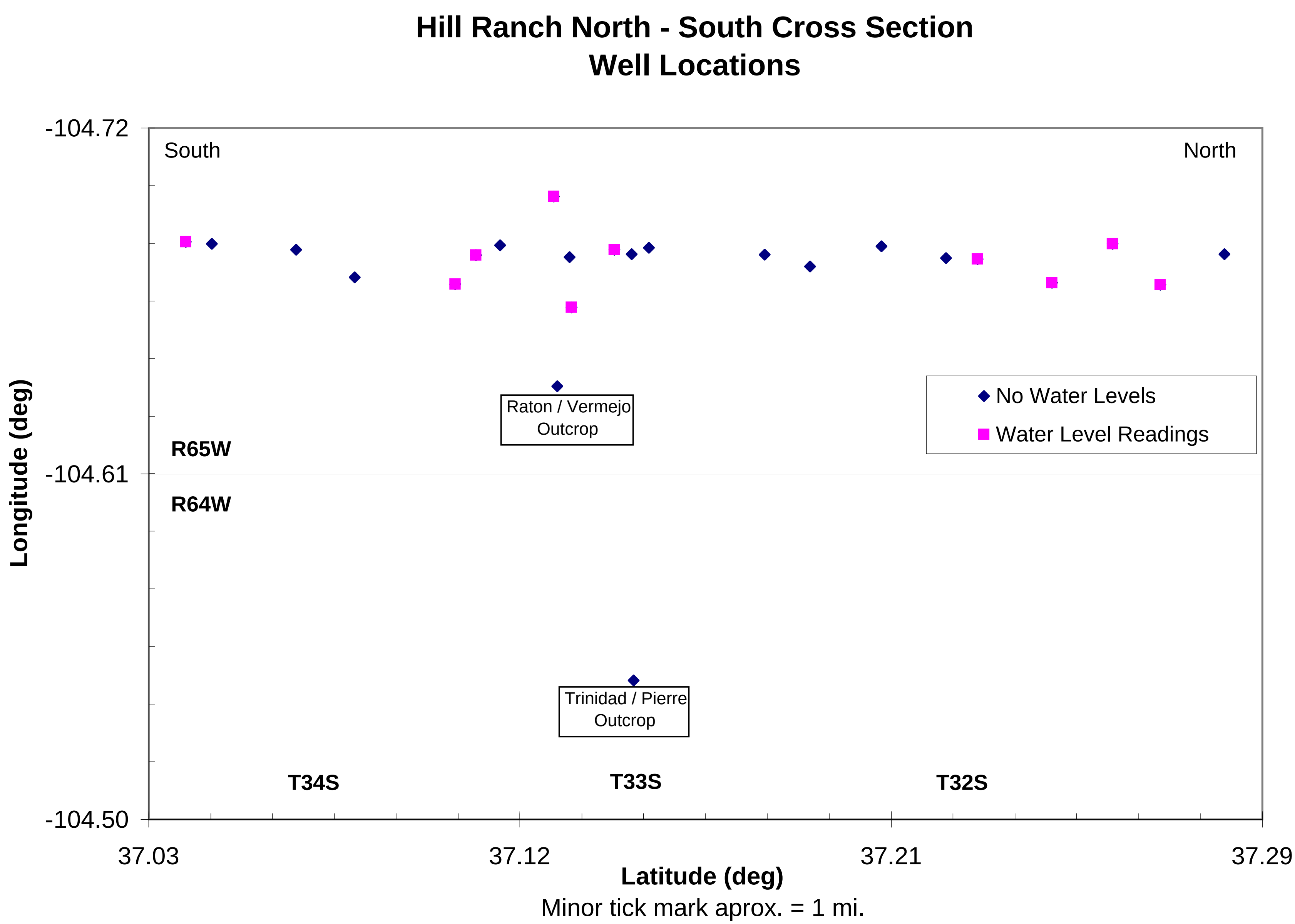
Hill Ranch Groundwater Classification

Exhibit C

North - South Cross Section



Hill Ranch North - South Cross Section
8,000
7,500
7,000
6,500
6,000
5,500
5,000
4,500
4,000
Elevation (ft)
South
North
Reilly
Canyon
Purgatoire
River
Surface
Raton / Vermejo Contact
Vermejo / Trinidad Contact
Estimated Trinidad Bottom / TD of CBM Well
CBM Well Top Perforation
CBM Well Bottom Perforation
Static Water Level from E-log
Raton / Vermeo Contact @ Purgatoire River
Trinidad / Pierre Contact @ Purgatoire River
T34S
T33S
T32S
37.03
37.12
37.21
37.29
Latitude (deg)
Minor tick mark aprox. = 1 mi.



N-S Cross Section.xls

TZA Water Engineers, Inc.

12/28/2007

Hill Ranch Groundwater Classification

Exhibit D

COGCC Sponsored Baseline Environmental Data Survey
prepared by Anthony W. Gorody

Hill Ranch Groundwater Classification

Exhibit E

<u>Dating Isotope Report, Raton Basin, Colorado</u>

prepared by Paul Oldaker

DATING ISOTOPE REPORT
RATON BASIN, COLORADO

PREPARED FOR:

CEDAR RIDGE LLC
484 TURNER DRIVE, BUILDING B
P. O. BOX 3524,
DURANGO, COLORADO
81302 USA

PREPARED BY:

MR. PAUL OLDAKER
HYDROLOGIST/HYDROGEOLOGIST
15 BALSAM COURT
P.O. BOX 775048
STEAMBOAT SPRINGS, COLORADO
80477 USA

21 FEBRUARY 2004

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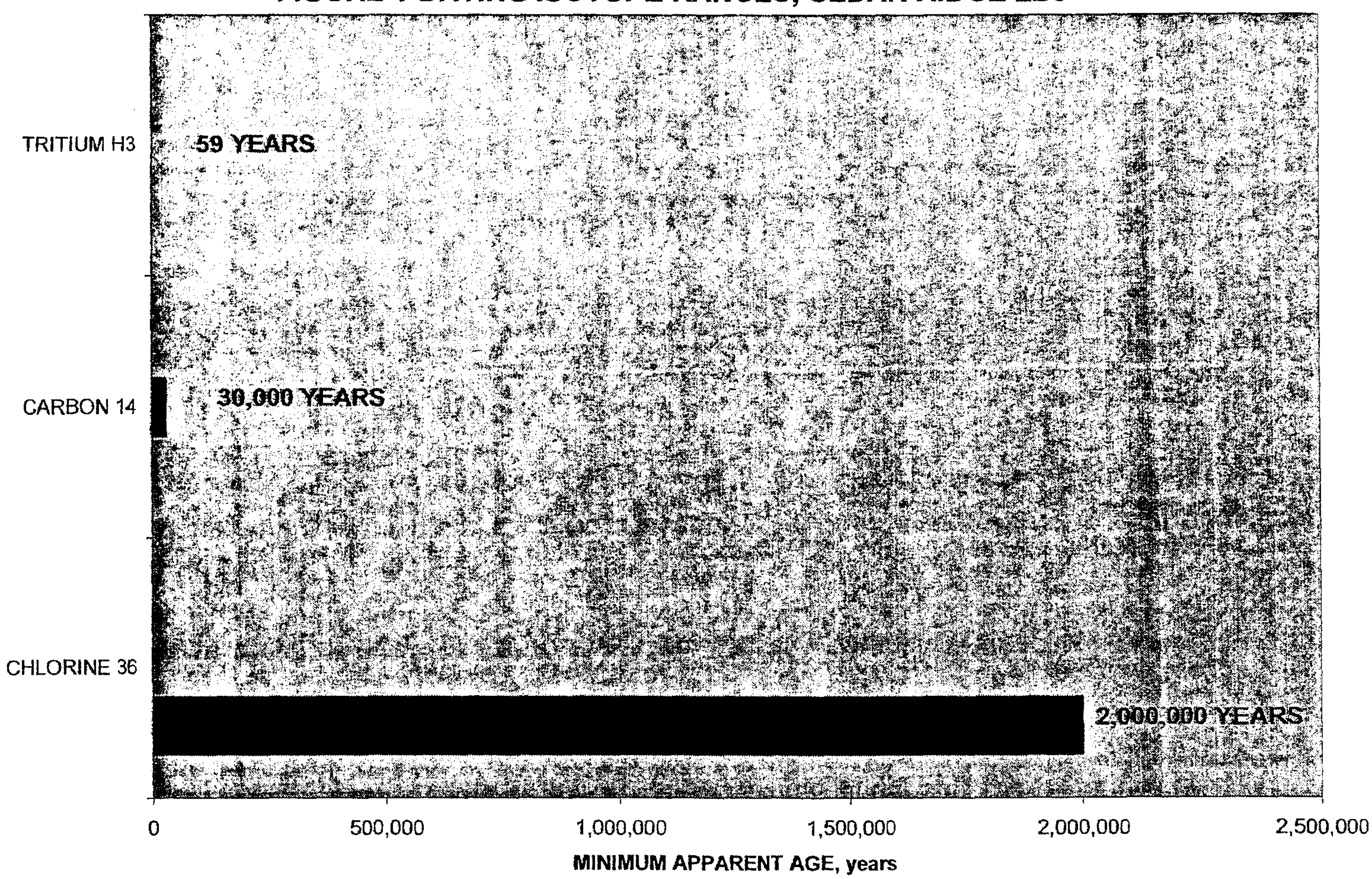
LIST OF FIGURES

INTRODUCTION

Cedar Ridge LLC is developing a coal bed methane (CBM) gas field to the northwest of Aguilar, Colorado. Dating of surface water, shallow ground water, and CBM waters provides a test on whether the shallow hydrologic system and the deeper CBM system are or are not hydraulically connected.

The three isotopes chosen for this study were tritium (H3), carbon 14, and chlorine 36. Their age ranges are shown on Figure 1. Tritium is used to date modern waters less than 60 years old. Carbon 14 is used to define waters less than 30,000 years old. Chlorine 36 is used to define waters less than 2,000,000 years old.

FIGURE 1-DATING ISOTOPE RANGES, CEDAR RIDGE LLC



SAMPLING

The Apishapa River was sampled on 11 September 2003. Twelve pre-cleaned 1 liter glass bottles with septa tops were filled using a long handled dipper. The location was at the county road bridge, just south of Aguilar.

Monitor Well 1 (MW-1) was sampled 11 September 2003. A portable Grundfoss sampling pump was set near the bottom of the well (90 feet). The well is one hundred feet deep. Twelve pre-cleaned 1 liter glass bottles with septa tops were filled.

The Turcotte 21-2 CBM well was sampled on 20 September 2002. The well was one of the original two in the Spring Creek pilot. Therefore it was pumping for the longest time. It also was the longest period of pumping since the pump was pulled. The result should be the best sample of Vermejo Formation CBM waters. The sample was collected from the wellhead in twelve pre-cleaned 1 liter glass bottles with septa tops.

All samples were taken of raw water before any treatment. Field parameters included temperature (Bimetal Thermometer), pH (Hanna Pocket), and specific conductance (Hanna Pocket). Specific conductance and pH were field calibrated using standard solutions.

ANALYSES

The samples for tritium analyses were sent to Geochron Laboratories. The Apishapa River and MW-1 samples were analyzed for low sensitivity (+/-3 TU). The Turcotte 21-2 CBM sample was analyzed for high sensitivity by enrichment (+/-0.11 TU).

The samples for carbon 14 analyses were sent to Geochron Laboratories. The Apishapa River and MW-1 samples were analyzed for a sensitivity of +/-60 years. There was no carbon 14 analysis for the Turcotte 21-2 CBM sample. The coal bed reservoir was deposited about 65,000,000 years ago. The carbon 14 has long ago decayed away. This large quantity of "dead carbon" could contaminate any sampling of reservoir waters and raise doubt as to the validity of any measured data. Therefore carbon 14 was not analysed for the coal bed methane sample.

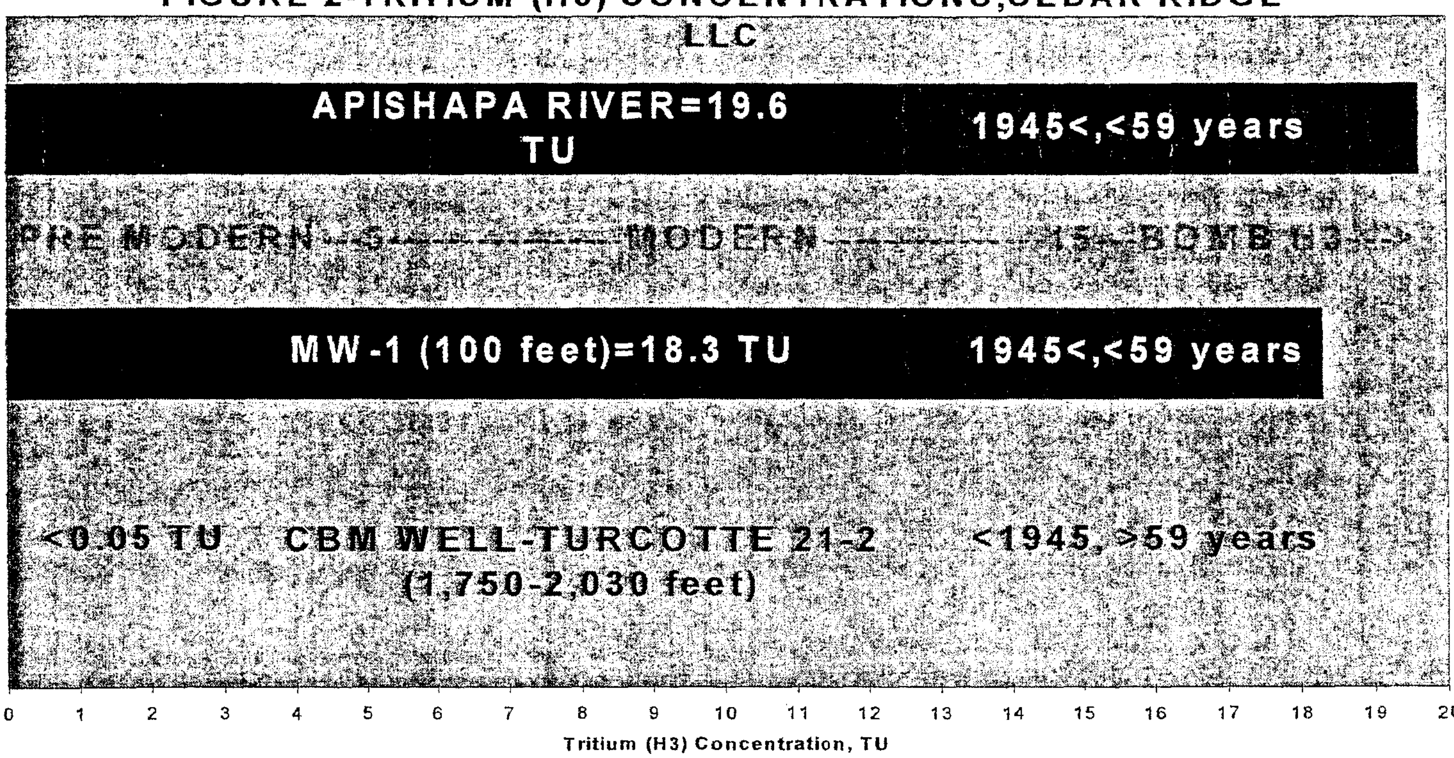
The sample for chlorine 36 analysis was prepared by Dr. Udo Fehn of the University of Rochester. The prepared sample was analyzed by Primelab at Purdue University. The sensitivity was +/-3.8 units of the chlorine ratio.

TRITIUM

Tritium is a hydrogen atom with two additional neutrons. It is rare in nature with the only natural source being the sun (cosmogenic). Since it has a short decay half life (12.43 years), only recent waters contain tritium. Tritium was also created as a byproduct of atmospheric atomic bomb testing starting in 1945 (59 years ago). Bomb test tritium significantly increased in 1951 with the advent of the hydrogen bomb. Tritium concentrations in precipitation peaked in the early 1960's. Concentrations have been declining through the present due to the cessation of atmospheric bomb testing.

The tritium concentrations measured for this project are shown on Figure 2. Clark and Aravena (2001) used the following classification for continental areas (also shown on Figure 2). From 0 to 5 TU is defined as pre-modern or before 1945 (>59 years). From 5 to 15 TU is defined as modern or after 1945 (<59 years). Greater than 15 TU is defined as having some tritium from the bomb testing.

FIGURE 2-TRITIUM (H3) CONCENTRATIONS,CEDAR RIDGE LLC



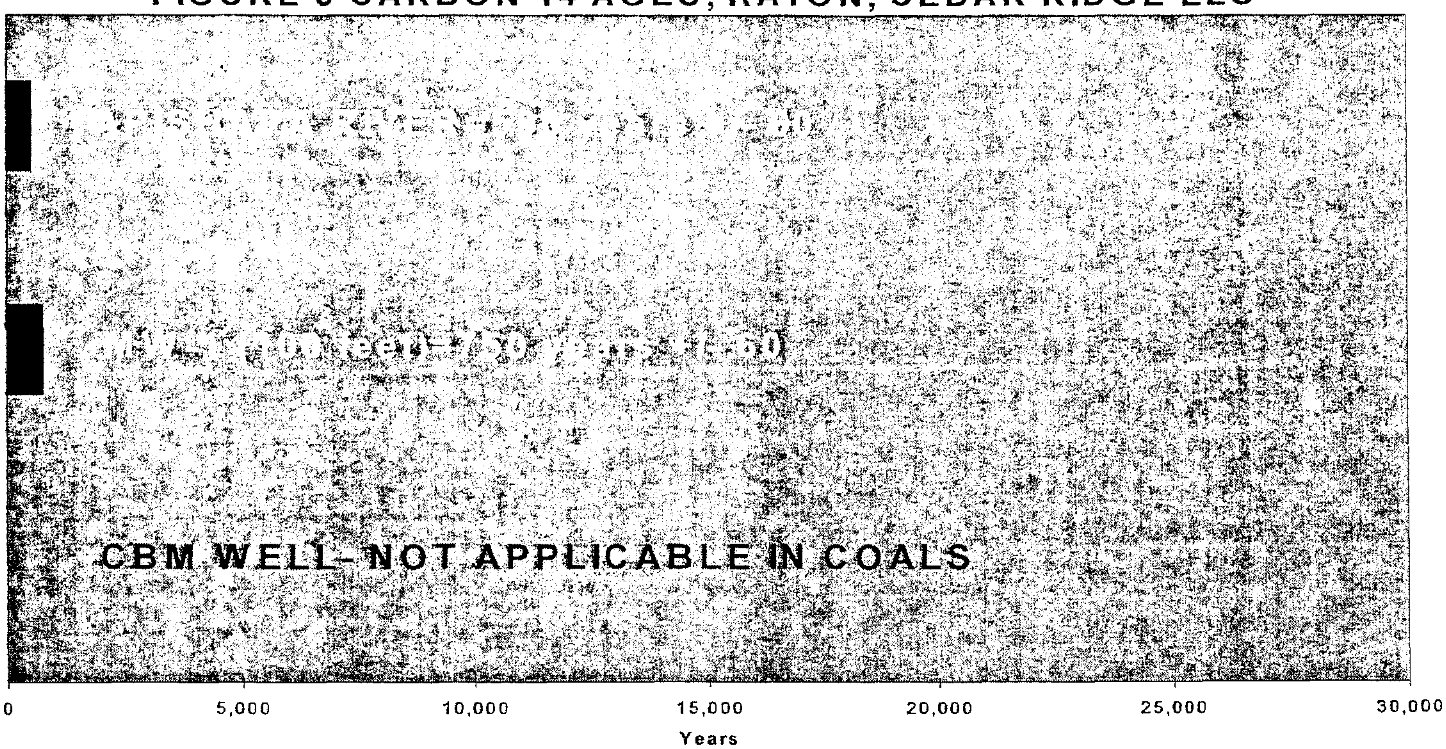
The Apishapa River and MW-1 tritium concentrations were greater than 15 TU so they are modern water that is younger than 59 years. MW-1 is 100 feet deep so this yields a vertical infiltration rate of 1.69 feet/year. Using this vertical infiltration rate it would take 1,183 years to get to 2,000 feet deep. The Turcotte 21-2 CBM tritium concentration is below the detection limit of <0.05 TU so it is less than 5 TU. It is pre-modern water that is older than 59 years.

CARBON 14

Carbon 14 is a carbon atom with two additional neutrons. It is used very commonly in archaeology. It has a decay half life of 5,730 years for a dating range of about 30,000 years. The Apishapa River and MW-1 samples were analyzed for carbon 14. The Turcotte 21-2 CBM sample was not analyzed for carbon 14 since the method is not applicable to coals. The coal bed reservoir was deposited about 65,000,000 years ago. The carbon 14 in the coals has long ago decayed away. This large quantity of "dead carbon" could contaminate any sampling of reservoir waters and raise doubt as to the validity of any calculated date. Therefore it was decided to not analyze for carbon 14.

The carbon 14 ages measured for this project are shown on Figure 3.

FIGURE 3-CARBON 14 AGES, RATON, CEDAR RIDGE LLC



The Apishapa River carbon 14 minimum apparent age was 500 years. The Monitor Well 1 (MW-1) carbon 14 minimum apparent age was 750 years. Both of these sources are of recent origin. MW-1 is 100 feet deep so this yields a vertical infiltration rate of 0.13 feet/year. Using this vertical infiltration rate it would take 15,385 years to get to 2,000 feet deep.

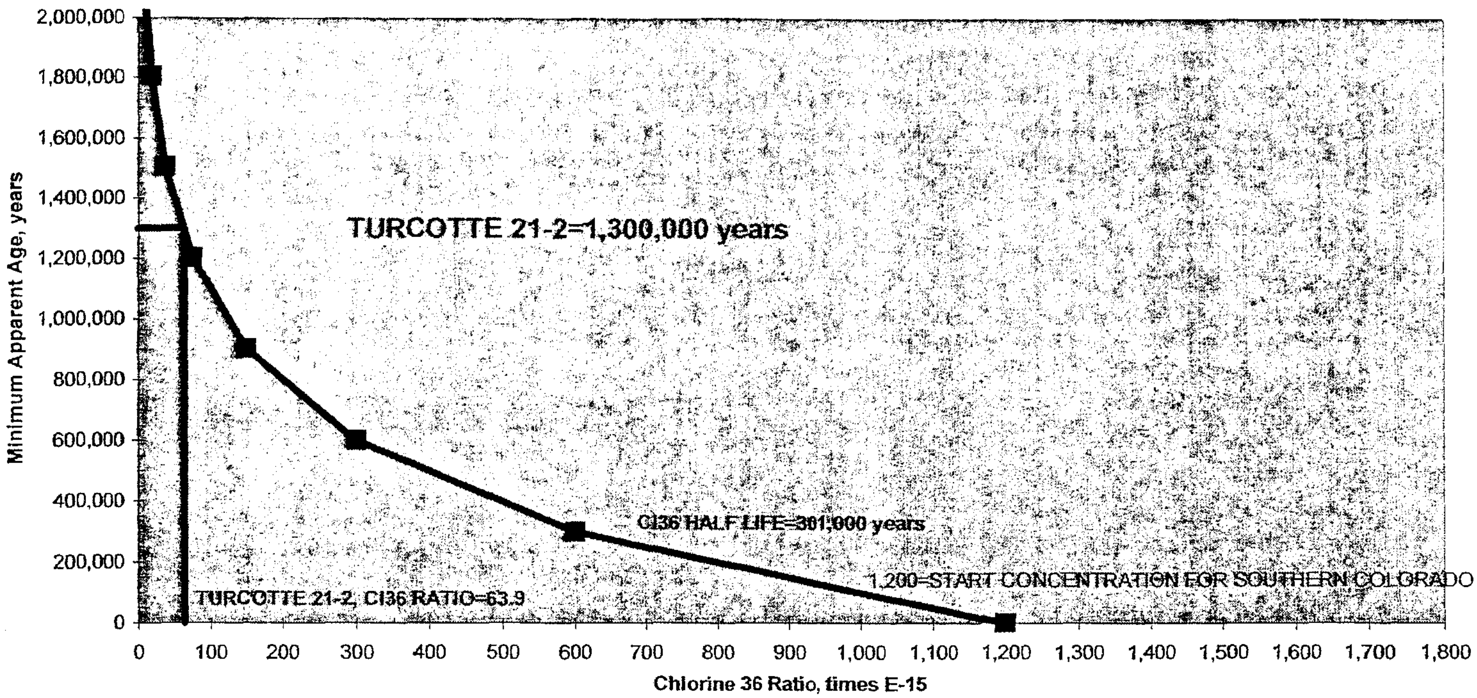
The carbon 14 ages are greater than that determined by tritium analysis. Some source of "dead carbon" has skewed the carbon 14 ages to be greater than the tritium ages. Most likely the "dead carbon" source was the coal in the watershed sediments.

CHLORINE 36

Chlorine 36 is a chlorine atom with one additional neutron. It has a decay half life of 301,000 years for a dating range of about 2,000,000 years.

The chlorine 36 concentration measured for the Turcotte 21-2 CBM well is shown on Figure 4. This is the first ratio for any well in the Raton Basin.

FIGURE 4- CHLORINE 36 DECAY CURVE AND AGE, CEDAR RIDGE LLC



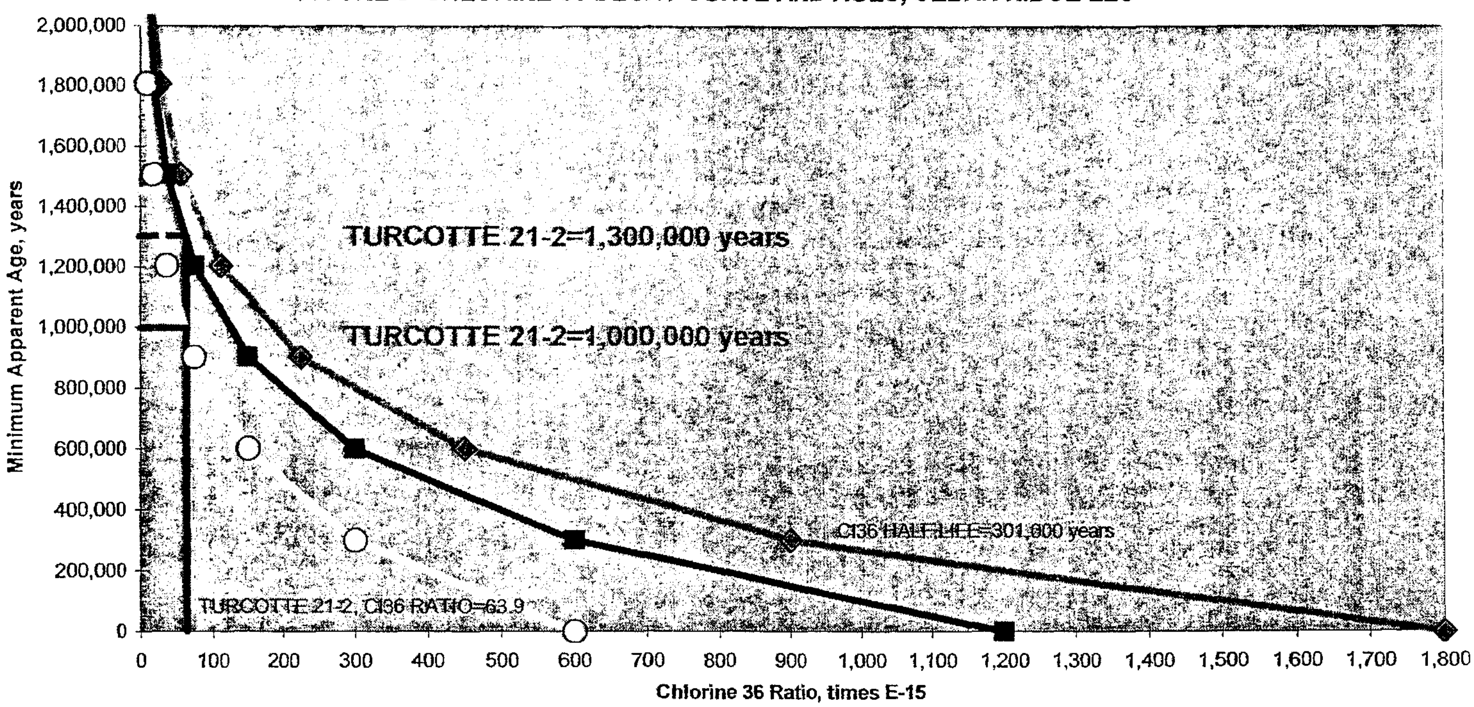
There is an extensive study of chlorine 36 ratio data for the Fruitland Formation in the San Juan Basin (Snyder et. al. 2003). The two basins are nearby, so the Turcotte result was compared to this data set since no data set exists for the Raton Basin. Thanks to the authors for providing their data set for the San Juan Basin.

The data ranges from below the detection limit to 1,800E-15. The estimated ratio for near surface or recharge waters (pre-anthropogenic) in southern Colorado is 1,200E-15 (Snyder et. al. 2003). Four samples from surface waters exceed this number reaching 1,840E-15. Qualitatively it is determined that a great deal of time has passed for the sample to decay from an estimated 1,200E-15 to 63.9E-15. This is ancient water and not recent or modern water.

Using the starting ratio of 1,200E-15, the decay rate half life of 301,000 years and the measured data of 63.9E-15 results in a minimum apparent age of at least 1,300,000 years. As stated before this is ancient water and not recent or modern water.

There are some factors which determine the variability around this age. The curve begins at 1,200E-15 which is the estimated ratio for surface or recharge waters in southern Colorado. This estimate may vary as shown by the data in Snyder et al. (2003). Northern New Mexico is estimated to be 600E-15. So the starting ratio for the decay curve may move the decay curve laterally as shown on Figure 5. At higher starting ratios the minimum apparent age is greater (more decay) and for lower starting ratios the minimum apparent age is less (less decay). This results in the ages varying from 1,000,000 to 1,430,000 years. Of course the measurement itself varies a further 3.8E-15.

FIGURE 5- CHLORINE 36 DECAY CURVE AND AGES, CEDAR RIDGE LLC



So the calculated minimum apparent age has some variability associated with it. I suppose it is safe to say that the age is at least 1,000,000 years. It is not an exact age since it has not been confirmed by a longer half life isotope result such as iodine 129 or helium 4. The author cannot determine a way that it could be much younger, recent, or modern. Therefore it is very unlikely that the CBM reservoir waters are hydraulically connected to surface waters since no recent or modern water was in the CBM reservoir water analysis.

This age in the millions of years is also much, much greater than the thousands of years calculated using vertical infiltration rates. This also indicates that there is no connection between surface waters and the CBM reservoir.

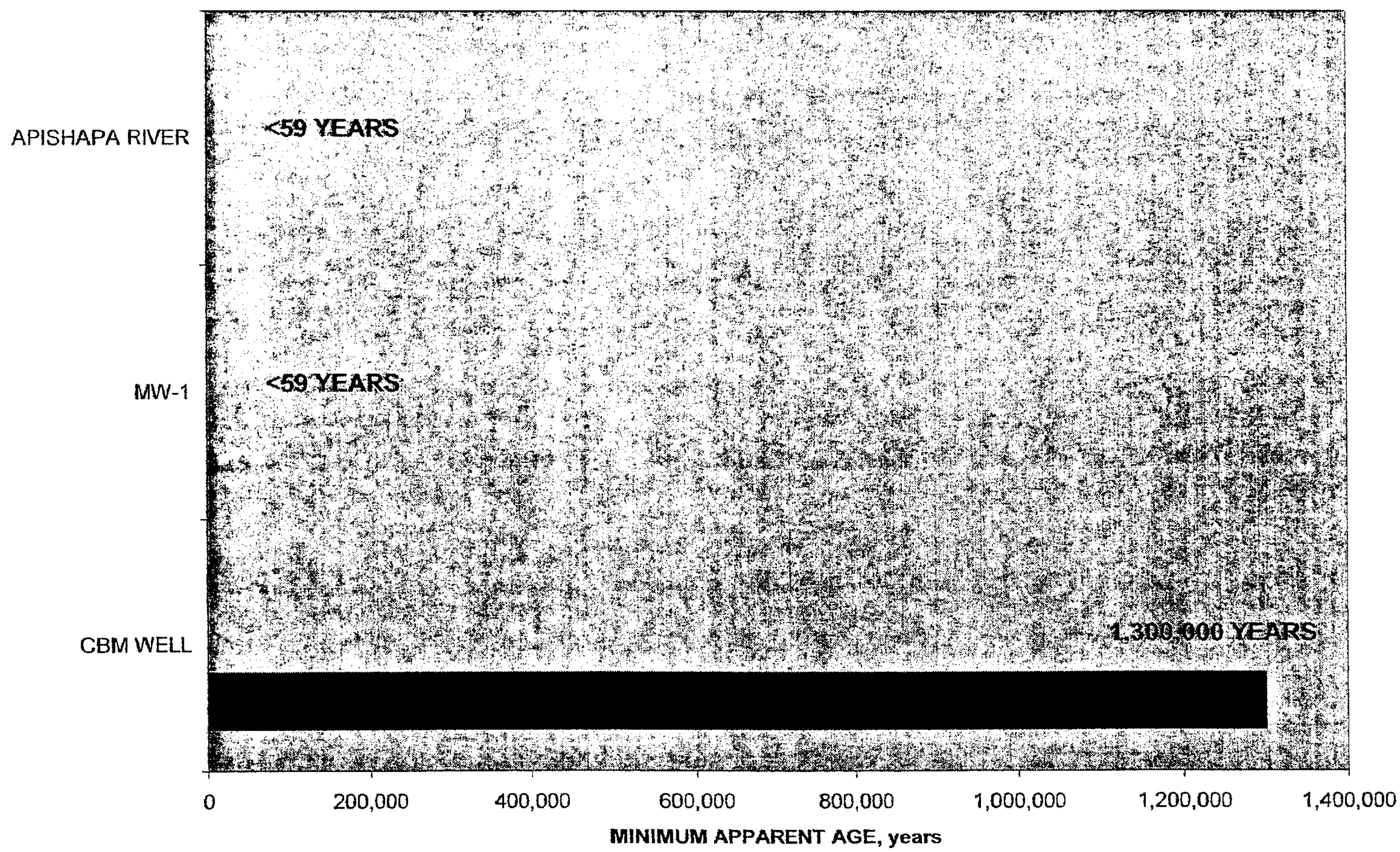
CONCLUSIONS

1. The Apishapa River and Monitor Well 1 are modern waters younger than 59 years ago (Figure 6).

2. The coal bed methane reservoir water sample was at least 1,000,000 years ago and could be much older (Figure 6).

3. The surface samples and the coal bed methane water sample came from separate and different sources. Therefore CBM reservoir water pumping is <u>not</u> from surface sources. The CBM reservoir is not currently being recharged from the surface. Shallow water systems cannot be contaminated by CBM pumping since they are not connected.

FIGURE 6- SUMMARY OF WATER AGES, CEDAR RIDGE LLC



REFERENCES

Clark, Ian and Ramon Aravena 2002
Environmental Isotopes in Ground Water Resources and Contaminant Hydrogeology, National Ground Water Association Short Course. Denver, Colorado, March 11-12, 2002. Authors Personal Files.

Gas Research Institute 1992
A Geologic Assessment of Natural Gas from Coal Seams in the Raton/Vermejo Formations, Raton Basin. Stevens, S.H., T. E. Lombardi, B.S. Kelso, and J. M. Coates, Topical Report GRI 92/0345. Authors Personal Files.

Gas Research Institute (Texas Bureau of Economic Geology, Kaiser et al.), 1994
Hydrogeology of the Raton/Vermejo Formations.

Geldon, A.L. 1989
Ground-Water Hydrology of the Central Raton Basin, Colorado and New Mexico, USDOI Geological Survey Water Supply Paper 2288. USDOI Geological Survey Library.

Howard, W. B. 1982
The Hydrogeology of the Raton Basin, Southcentral Colorado. Indiana University Masters Thesis. Authors personal files.

Johnson, R.B. 1983
Geologic Map of the Trinidad Quadrangle, South-Central Colorado, USDOI Geological Survey Miscellaneous Investigations Map I-558. USDOI Geological Survey Library.

Oldaker, P. R. 1988
Hydrogeologic Data Compilation and Analyses, Poison Canyon, Raton, Vermejo & Trinidad Formations, Raton Basin, Colorado, New Mexico. Unpublished report to Amoco Production Company (USA). COGCC Files.

Oldaker, P. R. 1995A
Timeline of Colorado Hydrocarbons Including Coal, Seeps, and Shallow Oil & Gas shows to 1927, Colorado School of Mines Second Symposium on Environmental Effects of Oil and Gas Operations. Arthur Lakes Library, Colorado School of Mines.

Oldaker, P. R. 1995B
Domestic Well Sampling Results, Report to Amoco Production Co. USA). Trinidad Public Library.

Oldaker, P. R. 1995C
Domestic Well Sampling Results, Colorado School of Mines Second Symposium on Environmental Effects of Oil and Gas Operations. Arthur Lakes Library, Colorado School of Mines.

Oldaker, P. R. 1997
Domestic Well Sampling Results, Report to Amoco Production Co. USA). Trinidad Public Library.

Oldaker, P. R. 2001
Ground Water Report, Report Prepared for Cedar Ridge LLC and the Colorado Oil and Gas Conservation Commission (COGCC). COGCC Files.

Snyder, G. T., W. C. Riese, S. Franks, U. Fehn, W. L. Pelzmann, A. W. Gorody, and J. E. Moran 2003
Origin and History of Waters Associated with Coal Bed Methane: Iodine 129, Chlorine 36, and Stable Isotope Results from the Fruitland Formation, CO and NM. Geochimica et Cosmochimica Acta, V.67, No.23, p4529-4544.

SECTION 3.0
RFP PIA-707
SCOPE OF WORK

3.1 Introduction

This document outlines a scope of work for carrying out analyses relating to current and potential future levels of stream depletion generated by removal of water by coalbed methane ("CBM") production wells. This study is a joint effort by the Colorado Oil and Gas Conservation Commission ("OGCC"), 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"). Note that while most of the tasks described below are in narrative format, there are a few items that are assumed to be self-explanatory in nature and not requiring narrative discussion. These items are simply listed by heading and enumerated in accord with the overall structure of this scope.

3.2 Purpose and Goals

The purpose of this study is 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 significant volumes of 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 throughout Colorado. This study seeks 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.

3.3 Scope/Focus Area

The analysis carried out under this scope of work will focus in the Raton and Piceance Basins of Colorado (see attached map). The overall analysis tasks to be included in this study are outlined in sections V through X below. The work product will be a comprehensive report presenting all analyses carried out, methods applied, assumptions, results, conclusions, and recommendations.

Sources of data that will be useful in carrying out the tasks involved in this study include, but are not limited to the following: OGCC website, databases, and library; DWR maps, publications and data bases; USGS maps, reports and other publications; Colorado Geological Survey maps and publications; Bureau of Land Management maps and publications; and Colorado Department of Public Health and Environment data. A similar study of stream depletions from CBM production titled, "Coalbed Methane Stream Depletion Assessment Study

– Northern San Juan Basin, Colorado" was completed in May 2006 (http://www.water.state.co.us/pubs/pdf/CMSDA_Study.pdf). It's content may be instructive for the present study. It is likely that other useful information will be available from other sources, but those listed herein are considered as being most applicable and are expected to significantly reduce the amount of additional data development necessary to conduct the needed analyses. As part of the work on this project, the data sufficiency and quality and the need, if any, for additional data to effectively carry out the study will be clearly assessed and described.

At this time, an analysis of a two-phase (i.e., gas and water) system will not be considered. Depending on the results of this study, it may be recommended that an additional study be performed using a two-phase model.

Please note that some of the following sections will be completed by CGS and should not be included in the contractor's bid for this project. Also, the consultant will complete some sections with assistance from CGS. The contractor should consider the cost of this arrangement in his bid for this project. All sections affected by the above statements are duly noted. Please see the summary table in section 3.14.

3.4 Communication/Outreach

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 people in the water resources community, oil and gas industry, environmental organizations, and of Colorado citizens with DNR and its respective agencies. The consultant who is selected for this study will need to successfully plan and coordinate public meetings between the industry and the respective agencies of DNR including any required presentations. There will be a minimum of two coordinated meetings, one at the beginning and one at the end of the study period, for each basin prior to the completion of this study.

3.5 Methodology

The depletion determination methodology applied to these analyses will be the analytical "Glover" methodology available in several formats. While it is recognized that the Glover methodology was developed for alluvial applications, it is considered to be the most easily applied tool for the level of study contemplated. The IDS "AWAS" program developed by Colorado State University is one acceptable tool for this analysis. If the hydrogeologic setting is appropriate, the methodology developed by S.S. Papadopulos and Associates for the DNR study, "Coalbed Methane Stream Depletion Assessment Study – Northern San Juan Basin, Colorado" may also be useful. The report generated for this study will include a discussion of the assumptions and limitations of the Glover methodology and the applicable programs as applied to the determinations that are the subject of this study. A comparison of these assumptions and limitations to the actual conditions and geometries encountered will be required.

3.6 Basin Analysis

This section of the scope details the analyses that will be required for the Raton and Piceance Basins in Colorado. The study report will document the analysis, presenting the data utilized, the limitations of such data, if any, the methodologies applied, the results, and a thorough discussion of any problems or issues encountered during the analysis that would have a bearing on the outcome of the analysis.

The analysis will include as a minimum the following items.

3.6 A. CBM Gas Production

The levels of CBM production will be researched and assessed. This will include the following specific aspects:

3.6 A.1. Current Levels
- a. Gas and Water Production
- b. Development of Correlations between Gas and Water Production

3.6 A.2. Estimated Future Production Levels
- a. Recent Production Trends and Projections

3.6 A.3. Well Densities and Distribution

3.6 B. Geology

The geology will be adequately characterized to facilitate the depletion analyses for as many wells as will be required to sufficiently determine the overall levels of depletion in rate and annual volume and the location or locations of nontributary areas within the basin. As a minimum the following items will be addressed and summarized in the report:

3.6 B.1. Basin Stratigraphy ***(to be completed by CGS)***

3.6 B.2. Target Producing Formations ***(to be completed by CGS)***

3.6 B.3. Formation Gas Pressures and Areas of Gas Discharge

It is recognized that the existence of higher gas pressure in the formations and gas discharge from the formation water can have an impact on the ability of water to infiltrate into the formation in any such areas. Accordingly, the study will require identification of any such areas and an assessment of the potential for elevated gas pressures or gas discharge to reduce or eliminate stream depletion where it otherwise might be occurring, based on all other factors.

3.6 B.4. Basin Geologic Structure ***(to be completed by CGS)***

3.6 B.5. Formation Outcrop Areas and Configuration ***(to be completed by CGS)***

3.6 B.6. Spatial Variation in Lithologies or Characteristics Bearing on CBM Production **(to be completed by CGS)**

3.6 C. Hydrogeology

The hydrogeologic characteristics pertinent to the depletion analyses will be thoroughly assessed for each differing hydrologic regime so that reliable depletion analyses can be carried out within the basin. With respect to the aquifer characteristics noted below, it is required that, assuming a range of values is developed, the values utilized in the actual depletion analyses runs, and ultimately applied be assessed for reasonableness and appropriateness. In addition, there will be required sensitivity analyses on each characteristic used in the analyses so that the level of potential variation in the results can be understood. The work under this category will include assessments, at a minimum, of the following items:

3.6 C.1 Identification of Regional Ground Water Flow Systems ***(to be***

completed by consultant with assistance from CGS)

3.6 C.1.a Characterize Regional Ground Water Flow Systems ***(to be completed by CGS)***

3.6 C.1.b Identify Target Intervals to be De-watered in Relation to Regional Ground Water Flow Systems ***(to be completed by CGS)***

3.6 C.1.c Identify Potential Flow Pathways Between Target Intervals and Aquifers or Tributary Surface Water Systems ***(to be completed by consultant with assistance from CGS)***

3.6 C.1.d Rank Potential Flow Pathways according to Potential to Impact to Tributary Water Within Regulatory Time Constraints ***(to be completed by consultant with assistance from CGS)***

3.6 C.2. Aquifer (or identified pathway) Characteristics

- 3.6 C.2.a. Hydraulic Conductivities
- 3.6 C.2.b. Saturated Thicknesses
- 3.6 C.2.c. Porosities and Specific Yield

3.6 C.3. Aquifer Extent and Boundary Conditions

- 3.6 C.3.a. Lateral and Spatial Extent
- 3.6 C.3.b. Nature of the Boundary, e.g., Outcropping at Surface or Fault Truncated, Etc.
- 3.6 C.3.c. Discharge Areas (springs or streams gaining via formation contact)
    1. Rate
    2. Volume

3.6 C.4. Water-Level Conditions

- 3.6C.4.a. Confined/unconfined
- 3.6 C.4.b. Pre-CBM flow conditions
- 3.6C.4.c. Surface Discharge
    1. Location
    2. Amount
        a. Rate
        b. Annual Volume

3.6 C.5 Evaluate Regional Ground Water Flow Systems for Implications of Ground Water Age Dates (from existing studies and literature) ***(to be completed by CGS)***

3.6 C.5 a. Estimate pre-CBM Travel Times Through Ground Water Flow Pathways

3.6 C.6. Surface Drainage Basins

The surface hydrology shall be characterized with respect to identification of the streams involved and the drainage basins associated with any such streams. The nature of the streams and their associated alluvial aquifers will be assessed with respect to flow conditions (perennial or intermittent), the nature, thickness and extent of the associated alluvial aquifer, the losing or gaining nature of the stream, and the alluvial water table. This work will also include identification of the administrative stream basins and whether or not these basins are considered by the Division of Water Resources as over- or under-appropriated. Discussion of whether any of the stream administration basins identified as under-appropriated might be reclassified as over-appropriated in the reasonable future is required.

3.6 C.7. Stream-aquifer Contact Areas

To carry out the depletion analyses, it is required that the stream-aquifer contact areas be accurately and thoroughly delineated. This work will also include determination as to whether any stream reaches may exhibit hydraulic break conditions. It is possible that at some locations the water table or potentiometric head within the aquifer (from which the water associated with CBM production is being removed) may currently be below the bottom of the streams and/or their associated alluvium at any points of contact with the target formation. In these instances, a hydraulic break has occurred and no subsequent CBM gas production-induced change in the water table or head in the formation can affect the stream flow or alluvial conditions. The existence of any areas where such a break has occurred can bear strongly on the identification of nontributary areas of the basin. (Note: Even though the water level has dropped below the alluvial system there will still be flow from the alluvial system to the underlying aquifer as long as there is hydraulic conductivity in the separating interval. If there is still a hydraulic connection the lowered water level just implies that there is a gradient to drive that flow. It certainly does not imply that the connection between the alluvial system and the deeper aquifer has been severed. What needs to be defined are areas where there is separation between the alluvial system and the underlying aquifer –or identified pathway-formed by strata with sufficiently low hydraulic conductivity that, even though there is a steep gradient, there is little potential for flow)

3.6 C.8. Water Quality

Water quality is a factor with respect to any current or future discharge to the stream system and with respect to the potential for utilizing water quality parameters, and total dissolved solids (“TDS”) in particular, as an indicator of possible recharge to the target formations from surface waters. Accordingly, this study will include characterization of the CBM production water quality and the water quality of the local stream systems identified as being in contact with the target formations. The data will be assessed with respect to any similarities or differences and with respect to whether the data indicates a potential recharge interconnection between the two sources.

3.6 D. Topographic Constraints/Considerations

The study will assess the impacts, if any, of topographic conditions on the potential for stream depletions and the impacts if any on the Glover depletion analyses carried out.

3.6 E. Glover Analyses

The Glover depletions analyses shall include sufficient number of runs to adequately characterize the current and estimated future levels of depletions to the surface stream system and to identify, as appropriate, any areas within the target formations that could be considered to be nontributary. The analyses and report will identify and fully describe the following items:

3.6 E.1. Geometry and Setup

3.6 E.2. The Aquifer Parameters Applied in Each Run

3.6 E.3. Magnitude of Depletions - Current Levels of Production
3.6.E.3.a. Depletions vs. Reduction in Accretion (Outflow)

3.6 E.4. Magnitude of Depletions - Estimated Future levels of Production

3.6 E.5. Estimate of Post-Pumping Depletions and Estimate of Recovery Time to Pre-CBM Conditions

3.6 E.6. Definition of Nontributary Areas

The assessment of areas determined to be nontributary under current conditions will also examine the possibility that such areas will be enlarged over time or that additional areas may in the future be designated as nontributary due to the influence of hydraulic breaks or other changes in the system having a bearing on the depletions.

3.6 E.7. Correlations

There is a possibility that the depletion analyses may allow for identification of correlations between certain geologic or hydrogeologic characteristics of the formations. Such correlations could provide valuable tools to simplify depletion assessments in similar areas or under future conditions. These possible correlations could include depletion vs. well producing zone/formation depth, depletions vs. aquifer transmissivity, depletions vs. the stream contact area, depletions vs. distance to the outcrop, or others, either singly or in combination. The study will thus require an assessment as to whether any such correlations appear to exist and discussion as to whether and how they might be applied.

3.6 F. Conclusions

The report generated for this study will include a summary of results, including maps of the geology, geologic structure, aquifer outcrop and stream contact areas, identified stream basins, Glover geometries and distances, locations of areas defined as nontributary, tables of depletions, water quality data for both the target formations and the surface stream waters, and any other data that would be useful and pertinent to the narrative discussions. The report shall also include discussions of changes to the systems as a result of water table or potentiometric head lowering, including ultimate limits to depletions as a result of hydraulic breaks and the potential for reductions in spring flows and any potential for water-quality related impacts on the surface stream system. Finally, the report shall also include for each basin a discussion of the potential impacts, if any, of formation gas pressure and/or gas discharge on the levels of stream depletions calculated.

3.7 Post-Pumping Ramifications

As part of this study, an assessment will be made as to the potential useful production life of the CBM wells and the estimated volume, rate and duration of post-pumping stream depletions or reductions in spring flow accretions. This determination will be presented and discussed in the report along with an assessment of the estimated collective impacts of the active and post-pumping depletions on the surface stream system.

3.8 Regulatory Framework

This task will involve an assessment of the current regulatory framework applicable to CBM wells and the production and disposal of water produced from these wells. Specifically, this section will address the roles of the OGCC and the DWR and the laws and rules governing the disposition of water produced by the CBM wells and the laws and rules relating to augmentation of stream depletions in over-appropriated basins. This work will also include an assessment as to how the roles of the various agencies might be changed if stream depletions are determined to be of a magnitude that could be resulting in injury to other water rights. As part of this work, the question of post-pumping depletions shall also be addressed with respect to the regulatory framework. Finally, this work will assess the role of CDPHE with respect to water quality and the potential impacts with respect to drinking water standards, stream standards or other applicable CDPHE rules or standards.

3.9 Potential Beneficial Uses of Discharged Wastewater

As part of this study the potential for beneficial use of the water produced by the CBM wells will be investigated. This assessment will address water quantity, water quality, the current disposition of water, the potential beneficial uses, both local and via stream conveyance, potential for exchange or use as augmentation water, and an overview of the potential positive and negative aspects of any such use, including economic considerations.

3.10 Interstate Ramifications

This task will involve a review and discussion of the various interstate compacts that could be affected by stream depletions and/or by changes in water quality as a result of CBM production, at both current and future estimated levels. This would include, but may not be limited to, the Arkansas River Compact, the Colorado River Compact, and the Upper Colorado River Compact. The analyses should reflect consideration of both water quantity and quality and how the current and estimated future levels of CBM production and calculated stream depletions could impact the provisions and restrictions of the compacts.

3.11 Rep ort: Results, Conclusions and Recommendations *(to be completed by consultant with assistance from CGS)*

The final report generated for this study will include a comprehensive assessment of all results and conclusions and will present recommendations as to the need for additional future data collection and /or depletion analyses. The consultant is responsible for producing 20 copies of the final report accompanied by data files created or compiled (e.g., Access, GIS, etc.) and any maps generated from these files.

3.12 Agency Review (to be completed by consultant with assistance from CGS, COGCC, DWR)

All draft reports will be reviewed by the CGS, OGCC, and the DWR prior to the final report being published. At a minimum, the first draft report must be prepared for agency review **by May 31, 2007** to allow for agency review, and subsequently, editing and correction by the contractor by June 30, 2007.

3.13 Timeline

This project and all work including the final report must be completed by June 30, 2007. The delivery location is 1313 Sherman Street, Denver, CO 80203.

3.14 Summary of Responsibilities

The table below summarizes the entity responsible for completing each task area of the study:

Task & Description	**Responsibility**
3.6 Basin Analyses	

3.6 A. CBM Gas Production	
3.6 A.1. Current Levels	Consultant
a. Gas and Water Production	Consultant
b. Development of Correlations between Gas and Water Production	Consultant
3.6 A.2. Estimated Future Production Levels	Consultant
a. Recent Production Trends and Projections	Consultant
3.6 A.3. Well Densities and Distribution	Consultant
3.6 B. Geology	
3.6 B.1. Basin Stratigraphy	CGS
3.6 B.2. Target Producing Formations	CGS
3.6 B.3. Formation Gas Pressures and Areas of Gas Discharge	Consultant
3.6 B.4. Basin Geologic Structure	CGS
3.6 B.5. Formation Outcrop Areas and Configuration	CGS
3.6 B.6. Spatial Variation in Lithologies or Characteristics Bearing on CBM Production	CGS
3.6 C. Hydrogeology	
3.6 C.1 Identification of Regional Ground Water Flow Systems	Primarily Consultant with CGS assistance
a. Characterize Regional Ground Water Flow Systems	CGS
b. Identify Target Intervals to be De-watered in Relation to Regional Ground Water Flow Systems	CGS
c. Identify Potential Flow Pathways Between Target Intervals and Aquifers or Tributary Surface Water Systems	Primarily Consultant with CGS assistance
d. Rank Potential Flow Pathways according to Potential to Impact to Tributary Water Within Regulatory Time Constraints	Primarily Consultant with CGS assistance
3.6 C.2. Aquifer (or identified pathway) Characteristics	Consultant
a. Hydraulic Conductivities	Consultant
b. Saturated Thicknesses	Consultant
c. Porosities and Specific Yield	Consultant
3.6 C.3. Aquifer Extent and Boundary Conditions	Primarily Consultant with CGS assistance
a. Lateral and Spatial Extent	Primarily Consultant with CGS assistance
b. Nature of the Boundary, e.g., Outcropping at Surface or Fault Truncated, Etc.	Primarily Consultant with CGS assistance
c. Discharge Areas (springs or streams gaining via formation contact)	Consultant
1. Rate	Consultant
2. Volume	Consultant
3.6 C.4. Water-Level Conditions	Consultant
a. Confined/unconfined	Consultant
b. Pre-CBM flow conditions	Consultant

c. Surface Discharge	Consultant
1. Location	Consultant
2. Amount	Consultant
a. Rate	Consultant
b. Annual Volume	Consultant
3.6 C.5 Evaluate Regional Ground Water Flow Systems for Implications of Ground Water Age Dates (from existing studies and literature)	CGS
a. Estimate pre-CBM Travel Times Through Ground Water Flow Pathways	Consultant
3.6 C.6. Surface Drainage Basins	Consultant
3.6 C.7. Stream-aquifer Contact Areas	Consultant
3.6 C.8. Water Quality	Consultant
3.6 D. Topographic Constraints/Considerations	Consultant
3.6 E. Glover Analyses	Consultant
3.6 E.1. Geometry and Setup	Consultant
3.6 E.2. The Aquifer Parameters Applied in Each Run	Consultant
3.6 E.3. Magnitude of Depletions - Current Levels of Production	Consultant
a. Depletions vs. Reduction in Accretion (Outflow)	Consultant
3.6 E.4. Magnitude of Depletions - Estimated Future levels of Production	Consultant
3.6 E.5. Estimate of Post-Pumping Depletions and Estimate of Recovery Time to Pre-CBM Conditions	Consultant
3.6 E.6. Definition of Nontributary Areas	Consultant
3.6 E.7. Correlations	Consultant
3.6 F. Conclusions	Consultant
3.7. Post-Pumping Ramifications	Consultant
3.8. Regulatory Framework	Consultant
3.9. Potential Beneficial Uses of Discharged Wastewater	Consultant
3.10. Interstate Ramifications	Consultant
3.11. Report: Results, Conclusions and Recommendations	Completed by Consultant with CGS, COGCC, DWR assistance
3.12. Agency Review	Completed by Consultant with CGS, COGCC, DWR assistance