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Conversion Factors and Vertical Datum

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
gallon (gal)	0.003785	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
gallon per year (gal/yr)	0.003785	cubic meter per year (m^3/yr)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Pressure[1]	
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Energy (natural gas) [2]	
British thermal unit (Btu)	1,054.18	joules (J)
cubic foot (ft^3)	1,082,643	joules (J), (approximate)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

[1]The pressure at the bottom of a 1-foot-high column of water, at 4ºC, is 0.433515 pounds per square inch (The Chemical Rubber Company, 1973).

[2]The energy in 1 cubic foot of natural gas is approximately equivalent to 1,027 British thermal units (American Gas Association, 2006).

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

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Abstract

The Raton Basin in southern Colorado and northern New Mexico is undergoing increased development of its coalbed-methane resources. Annual production of methane from coalbeds in the Raton Basin in Huerfano and Las Animas Counties, Colorado, increased from about 28,000,000 thousand cubic feet from 478 wells to about 80,000,000 thousand cubic feet from 1,543 wells, during 1999–2004. Annual ground-water withdrawals for coalbed-methane production increased from about 1.45 billion gallons from 480 wells to about 3.64 billion gallons from 1,568 wells, during 1999–2004. Where the coalbeds are deeply buried near the center of the Raton Basin, water pressure may be reduced as much as 250 to 300 pounds per square inch to produce the methane from the coalbeds, which is equivalent to a 577- to 692-foot lowering of water level. In 2001, the U.S. Geological Survey, in cooperation with the Colorado Water Conservation Board, began an evaluation of the potential effects of coalbed-methane production on the availability and sustainability of ground-water resources.

In 2003, there were an estimated 1,370 water-supply wells in the Raton Basin in Colorado, and about 90 percent of these water-supply wells were less than 450 feet deep. The tops of the production (perforated) interval of 90 percent of the coalbed-methane wells in the Raton Basin (for which data were available) are deeper than about 675 feet. The potential for interference of coalbed-methane wells with nearby water-supply wells likely is limited because in most areas their respective production intervals are separated by more than a hundred to a few thousand feet of rock. The estimated vertical separation between production intervals of coalbed-methane and water-supply wells is less than 100 feet in an area about 1 to 6 miles west and southwest of Trinidad Lake and a few other isolated areas. It is assumed that in areas with less than 100 feet of vertical separation, production by coalbed-methane wells has a greater potential for interfering with nearby water-supply wells. More detailed geologic and hydrologic information is needed in these areas to quantify the potential effects of coalbed-methane production on water levels and the availability and sustainability of ground-water resources.

Introduction

The Rocky Mountain region contains several sedimentary provinces with extensive coal deposits and significant accumulations of coalbed gas (Schenk and others, 2001). Production of coalbed gas, which is referred to as "coalbed methane" (CBM), carries with it some technological and environmental difficulties and costs. Unlike conventional oil or gas reservoirs, water permeates coalbeds, and water pressure compresses and traps gas within the coal (Schenk and others, 2001). To produce the gas (methane) from coal, water must be drawn off first to lower the fluid pressure so methane can flow out of the coal and to the well bore (Nuccio, 2000). Reduction of fluid pressure for CBM production can affect the availability and sustainability of local ground-water supplies. If water wells are completed in coalbeds or coalbeds are hydraulically connected with aquifers in which water wells are completed, CBM production may interfere with nearby water-supply wells.

The Raton Basin in southern Colorado and northern New Mexico (fig. 1) is undergoing increased development of its coalbed-methane resources. Production of methane from coalbeds in the Raton Basin in Huerfano and Las Animas Counties, Colorado (fig. 1), increased substantially during 1999–2004. About 28,000,000 thousand cubic feet (Mcf) of CBM was produced from 478 wells during 1999 and about 80,000,000 Mcf was produced from 1,543 wells during 2004 in the Raton Basin in Colorado (fig. 2) (Colorado Oil and Gas Conservation Commission, 2005). Ground-water withdrawals by CBM wells in Huerfano and Las Animas Counties increased from about 1.45 billion gallons from 480 wells, during 1999, to about 3.64 billion gallons from 1,568 wells, during 2004 (fig. 2) (Colorado Oil and Gas Conservation Commission, 2005). Because of the increased withdrawals of ground water for CBM production, water-well owners

Figure 1. Location of the study area.

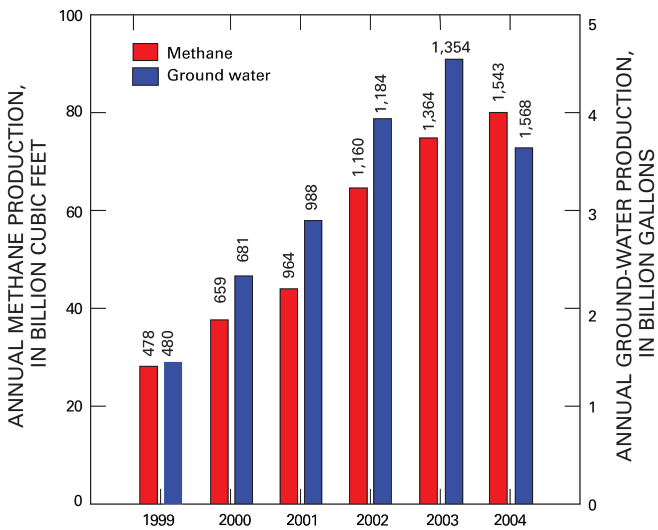

Figure 2. Annual production of coalbed methane and ground water in the Raton Basin, Huerfano and Las Animas Counties, Colorado, 1999–2004.

and resource managers are concerned that the reductions of fluid pressure in the coalbeds could affect nearby water-supply wells and the availability and sustainability of local ground-water supplies. In 2001, the U.S. Geological Survey, in cooperation with the Colorado Water Conservation Board, began a preliminary evaluation of the potential effects of CBM production on the availability and sustainability of ground-water resources.

Purpose and Scope

This report presents results from a preliminary evaluation of the vertical separation between production intervals of CBM wells and nearby water-supply wells in the Raton Basin, in Huerfano and Las Animas Counties, Colorado. Data for more than 1,600 oil and gas wells in Huerfano and Las Animas Counties were retrieved from the database of the Colorado Oil and Gas Conservation Commission at *http://www.oil-gas.state.co.us*. Data for more than 2,000 water wells in Huerfano and Las Animas Counties, Colorado, were retrieved from the Colorado Division of Water Resources at *http://water.state.co.us* (Colorado Division of Water Resources, 2003). [Note: Well data can no longer be retrieved from the Colorado Division of Water Resources Web site.]

Hydrogeologic Setting

The Raton Basin is an asymmetrical trough in southern Colorado and northern New Mexico that contains several thousand feet of coal-bearing clastic sedimentary rocks, primarily sandstone, siltstone, shale, and conglomerate (fig. 3, from Flores and Bader, 1999). Coalbeds in the Raton and Vermejo Formations are the primary targets for CBM development in the Raton Basin. The Raton and Vermejo Formations and the Trinidad Sandstone, which underlies the Vermejo Formation, also are sources of ground water for many water-supply wells in the Raton Basin (Geldon, 1989). Most ground-water flow in the Raton-Vermejo-Trinidad aquifer (Geldon, 1989) occurs in sandstones and thick coal seams, but fractured siltstone and shale also transmit water. Regional ground-water flow in the Raton-Vermejo-Trinidad aquifer is from west to east but is deflected towards stream valleys (Abbott and others, 1983; Geldon, 1989). Locally, igneous intrusions (dikes) may form barriers to ground-water flow (Geldon, 1989). Flow paths within the Raton-Vermejo-Trinidad aquifer and overlying aquifers are complex because of the effects of geology and topography.

Depths of Water-Supply Wells and Production Intervals of Coalbed-Methane Wells

In 2003, there were an estimated 1,370 water-supply wells in the Raton Basin in Colorado, and about 90 percent of these water-supply wells were less than 450 feet deep (Topper and others, 2003). Because the tops of the production (perforated) interval of 90 percent of the CBM wells in the Raton Basin (for which data were available) are deeper than about 675 feet, areas in which production intervals of CBM and water-supply wells overlap are limited. Typically, a well screen or perforated casing is installed in the production interval of a water-supply well and plain casing is installed

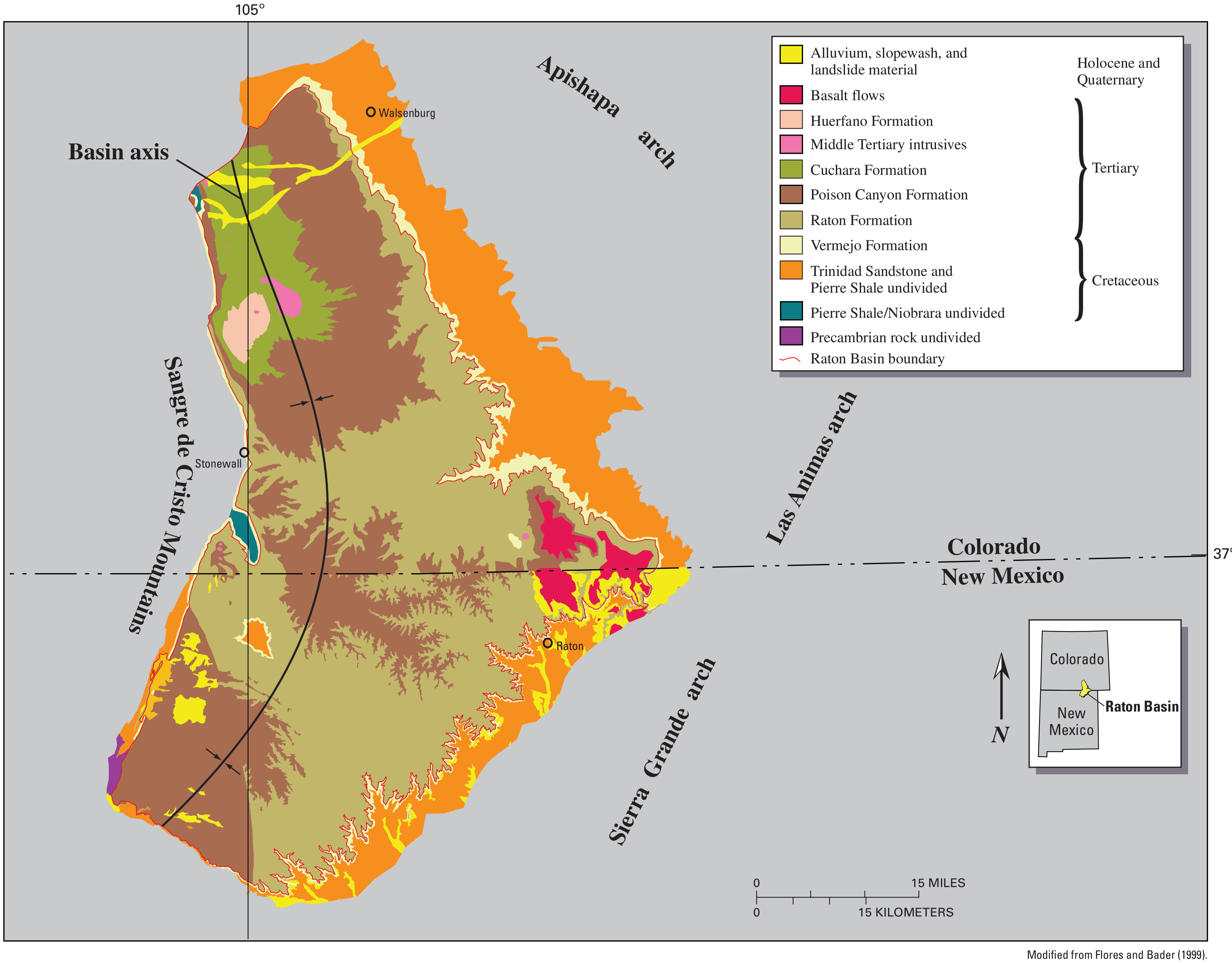

Figure 3. Generalized geologic map of the Raton Basin, Colorado and New Mexico.

above the production interval. Except for a mandatory surface (sanitary) seal, water-supply wells typically are not cemented (grouted) above the production interval, unless another aquifer overlies the producing aquifer. A typical CBM well is drilled, cased, and cemented through overlying strata and the potential production interval (Colorado Oil and Gas Conservation Commission, variously dated). The casing of a CBM well is perforated in selected intervals that contain coal seams, and the coal seams may be hydraulically fractured to increase permeability of the production interval. The casing and cement are designed to prevent hydraulic connection between the perforated and nonperforated intervals in the annular space between the borehole and casing of the CBM well.

Ground-Water Pumping

Annual ground-water pumping for domestic, irrigation, and municipal supplies in Huerfano and Las Animas Counties was an estimated 1.7 billion gallons in 2000 (Hutson and others, 2004), which is equivalent to about 47 percent of 3.64 billion gallons that was produced by 1,568 CBM wells in the Raton Basin during 2004. Generally in Colorado, the annual rate of withdrawal for a household well on less than 35 acres is limited to 0.33 acre-foot and the limit for a domestic well on 35 or more acres is 1 acre-foot (Colorado Division of Water Resources, 2005). Annual withdrawals of 0.33 and 1 acre-foot are equivalent to average pumping rates of about 0.21 and 0.62 gallon per minute, respectively. During 2004, combined production of ground water by 1,568 CBM wells in the Raton Basin was about 3.64 billion gallons. The average pumping rate for CBM production well in the Raton Basin of Colorado during 2004 was about 4.4 gallons per minute [3.64 billion gallons per year ÷ (365 days per year * 1,440 minutes per day * 1,568 wells) ≈ 4.4 gallons per minute per well].

Typically, as CBM production proceeds, the ratio of produced gas (methane) to water is smallest during initial phases of development, when water pressure in the coalbeds is being reduced and the volume of ground water produced with gas is large. The ratio of gas to water increases with time, as the volume of produced gas increases and produced ground water decreases, until the gas production decreases as the storage is depleted (Kuuskraa and Brandenberg, 1989). Based on the available data (fig. 2), it appears that the Raton Basin is still in the initial or depressurization phase of development. As fluid pressure in the CBM production intervals decreases, the cumulative annual withdrawal of ground water by CBM wells in the Raton Basin is expected to decrease, unless more CBM wells are brought into production.

Ground water produced by CBM wells in the Raton Basin generally is not returned to the intervals from which it was pumped. There are several methods used for disposal of CBM-produced water in the Raton Basin, including injection into deeper geologic units, discharge to surface drainages, and discharge to lined (evaporation) or unlined (recharge) pits (Colorado Oil and Gas Conservation Commission, 2000). Some CBM-produced water also is used for dust suppression on unpaved roads. CBM-produced water that is discharged at the surface or in recharge pits may recharge shallow aquifers. CBM production could deplete ground-water storage in the coalbeds, unless additional recharge is captured and (or) discharge is intercepted.

Vertical Separation between Production Intervals of Coalbed-Methane Wells and Water-Supply Wells

When fluid (water or gas) pressure in an aquifer (coalbed) is reduced at a CBM well, the flow of fluid will increase from areas of greater potential toward the CBM well. The rate of flow toward a CBM well and the effects on fluid pressure in the area around the well are controlled by the permeability and storage properties of the coal and surrounding rocks, the physical properties of the fluid (gas and water), and the amount and duration of pressure reduction at the CBM well. Because the permeability of stratified sedimentary rocks generally is greater parallel to bedding than across bedding, it is assumed that CBM production likely would have the greatest potential for interfering with nearby water-supply wells, in areas in which there is no or little vertical separation between their respective production intervals.

Potential Changes in Water Levels Resulting from Coalbed-Methane Production

In general, the fluid pressure (water level) in the coalbeds is reduced to attain a water level above the top of the perforated interval of the CBM production well. Where the coalbeds are deeply buried near the center of the Raton Basin, fluid pressure may be reduced as much as 250 to 300 pounds per square inch. The pressure exerted by a 1-foot-tall column of water, at 4ºC, is 0.433515 pounds per square inch (The Chemical Rubber Company, 1973). Thus, a fluid-pressure reduction of 250 to 300 pounds per square inch is equivalent to a reduction of water level of approximately 577 to 692 feet. Reductions in fluid pressure (water level) in CBM production wells that are located nearer the outcrop of the coalbeds likely are less than fluid-pressure reductions in wells in areas where the coalbeds are deeply buried. Because changes in fluid pressure (water level) in an aquifer are inversely proportional to the distance squared from the pumped well (Theis, 1935), the largest changes in fluid pressure (water level) will occur in the production intervals (coalbeds) near the CBM wells, and changes will decrease exponentially away from the production wells. Because changes in fluid pressure (water level) in an aquifer are proportional to the rate and duration of pumping, changes will be greatest near the CBM wells that produce the most water. Changes of fluid pressure (water level) resulting from pumping also are a function of the hydraulic and storage properties of the rocks and may be affected by flow barriers (faults and dikes) and leakage from or through overlying and underlying rocks. Quantitative estimates of the change in fluid pressure (water level) caused by pumping a CBM well require detailed knowledge of the production history of the well, hydraulic and storage properties of the coalbeds and adjacent rocks, and distances to hydraulic boundaries (barriers or sources).

Hypothetical Effects of Coalbed-Methane Production on Nearby Water-Supply Wells

A simplified schematic diagram (fig. 4) illustrates why water levels in some water-supply wells could be affected by CBM production while other nearby wells are not affected. Pumping by a hypothetical CBM well (fig. 4, well B) might not cause water-level declines in (interfere with) a nearby water-supply well (fig. 4, well A) if the vertical separation of production intervals of a CBM well and a water-supply well is large and the intervening rock is unfractured and relatively impermeable siltstone and shale. Pumping by a CBM well (fig. 4, well B) might interfere with a nearby water-supply well if the intervening rock is relatively permeable coal, sandstone, or fractured siltstone and shale (fig. 4, well C) or the vertical separation of production intervals is small (fig. 4, well D). Pumping by a CBM well (fig. 4, well B) eventually could interfere with more distant water-supply wells (fig. 4, wells E and F), if the CBM well and the water-supply wells are completed in the same interval and pumping by the CBM well is large and continues for an extended period. Flow barriers (not shown in fig. 4) formed by changes in lithology (facies changes), vertical offsets of bedding at faults, or intrusive rocks (dikes) also may affect water-level changes in water-supply wells due to pumping CBM wells, depending on the location of the flow barriers relative to the CBM and water-supply wells.

Estimated Vertical Separation between Production Intervals of Coalbed-Methane and Water-Supply Wells

The potential for interference of CBM production wells with water-supply wells likely is greatest in areas where the CBM wells and water-supply wells are producing from the same interval or there is little vertical separation between their respective production intervals. The generalized thickness of the rock separating the production intervals of CBM wells and nearby (within 1 mile) water-supply wells is shown in figure 5. The minimum vertical separation (fig. 5) of "0 to 100 feet" is an arbitrary limit and does not imply that 100 feet is the vertical separation needed to prevent interference between CBM wells and nearby water-supply wells. Figure 5 was created, using a geographic information system, by comparing the altitudes of the top and bottom of production intervals of CBM wells with the altitude of the bottom of water-supply wells. Altitudes of the production intervals of CBM wells were calculated from the reported land-surface altitude at and depths to the top and bottom of the perforated intervals of CBM wells (Colorado Oil and Gas Conservation Commission, 2005). About one-third of the CBM wells in the Raton Basin were not used in preparation of figure 5 because production intervals were not available for these wells. Altitudes of the bottom of the water-supply wells were calculated as the altitude of the land surface at a well, as estimated from the 1-Arc-second National Elevation Dataset (U.S. Geological Survey, 2004), minus the depth to the bottom of the well (Colorado Division of Water Resources, 2003). [One Arc-second is approximately a distance of about 30 meters or 98 feet.] Because local relief of the land surface may be several hundred feet in the Raton Basin and the location of a water-supply well may be accurate only to the nearest 40-acre tract, errors in well location could be as large as about 934 feet and could result in large errors in the estimated altitude of the land surface.

In most of the Raton Basin in Colorado, the potential for interference of CBM wells with nearby water-supply wells likely is limited because the production intervals of CBM wells and nearby water-supply wells, in most areas, are separated by hundreds to a few thousand feet of rock (fig. 5). Locally, in an area about 1 to 6 miles west and southwest of Trinidad Lake and a few other isolated areas (fig. 5), the estimated vertical separation between production intervals of CBM and water-supply wells is less than 100 feet. It is assumed that in these areas, pumping of CBM wells has a greater potential for interfering with nearby water-supply wells; however, more detailed geologic and hydrologic information is needed in these areas to estimate the potential effects of CBM production on water levels.

Additional data that are needed to better understand the effects of CBM development on the availability and sustainability of ground-water resources in the Raton Basin of Colorado include better definitions of the hydrostratigraphic framework (three-dimensional geometry) and the hydraulic and storage properties of the aquifers and confining units, the production characteristics and perforated intervals of CBM and water-supply wells, and the monitoring of fluid pressures and water levels in CBM and water-supply wells.

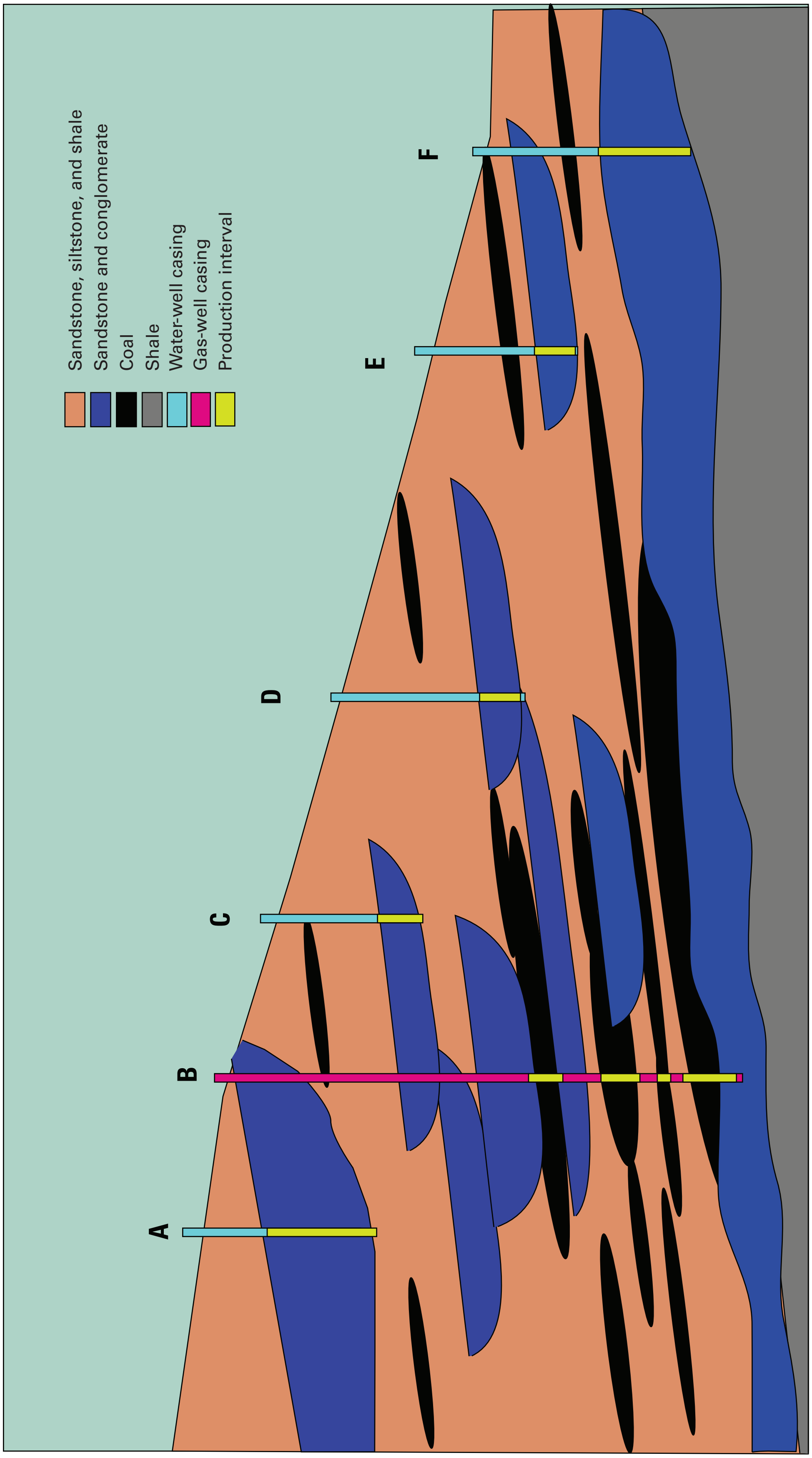

Figure 4. Hypothetical hydraulic connections between production zones of a coalbed-methane well and nearby water-supply wells.

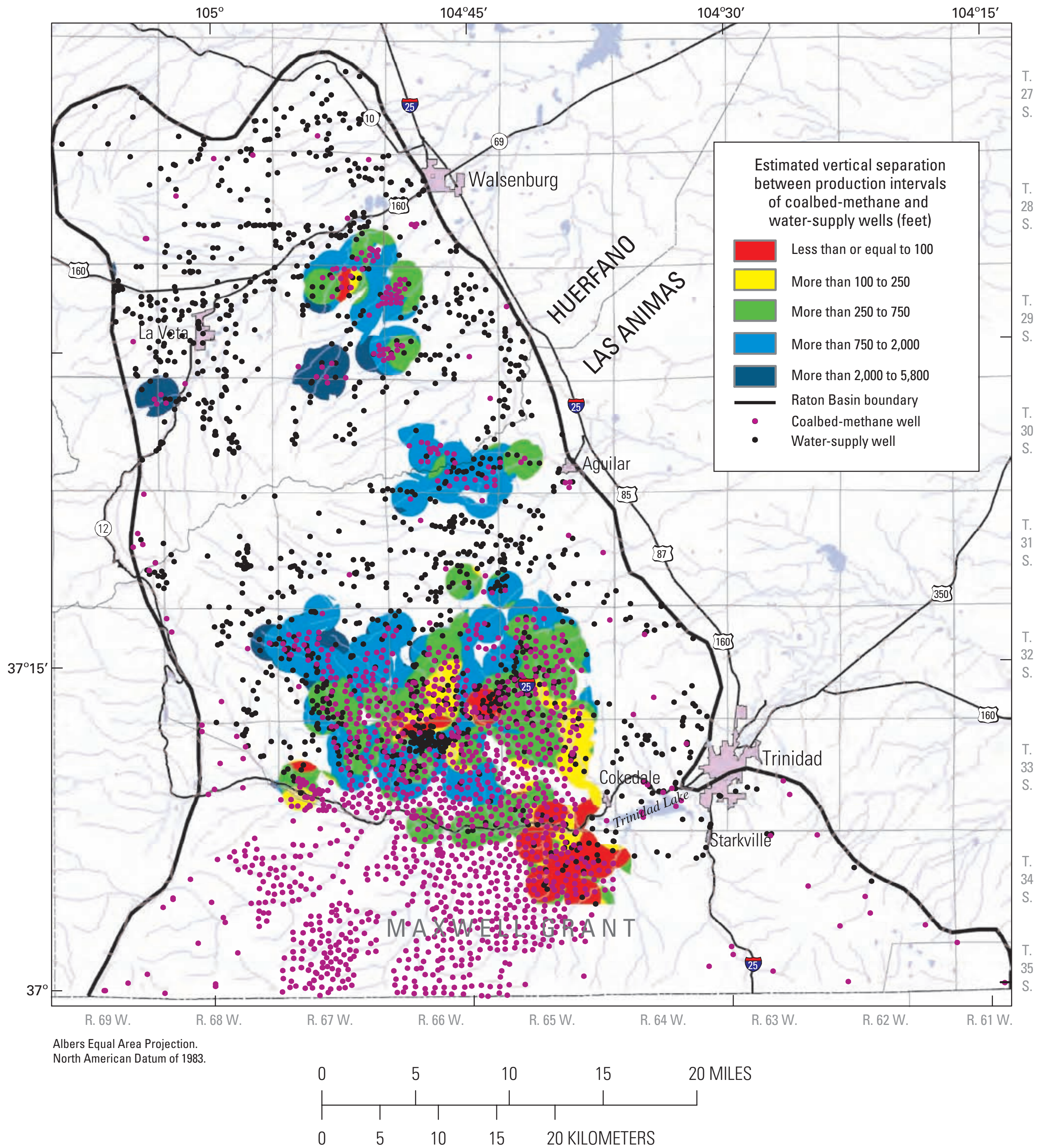

Figure 5. Estimated vertical separation between production intervals of coalbed-methane and water-supply wells in the Raton Basin, Huerfano and Las Animas Counties, Colorado, 1999–2004.

Summary

Reduction of fluid pressure for coalbed-methane production can affect the availability and sustainability of local ground-water supplies. Coalbed-methane production has a greater potential for interference with nearby water-supply wells, if the water wells are completed in the coalbeds or in aquifers that are hydraulically connected with the coalbeds. Production of coalbed methane increased substantially during 1999–2004 in the Raton Basin in Huerfano and Las Animas Counties, Colorado. About 28,000,000 thousand cubic feet of coalbed methane was produced from 478 wells during 1999 and about 80,000,000 thousand cubic feet was produced from 1,543 wells during 2004 in the Raton Basin in Colorado. Ground-water withdrawals by coalbed-methane wells in Huerfano and Las Animas Counties increased from about 1.45 billion gallons from 480 wells, during 1999, to about 3.64 billion gallons from 1,568 wells, during 2004. Where the coalbeds are deeply buried near the center of the Raton Basin, fluid pressure may be reduced as much as 250 to 300 pounds per square inch, which is equivalent to a reduction of water levels of approximately 577 to 692 feet. Water-well owners and resource managers are concerned that the reductions of fluid pressure in the coalbeds could affect nearby water-supply wells and the availability and sustainability of local ground-water supplies. In 2001, the U.S. Geological Survey, in cooperation with the Colorado Water Conservation Board, began an evaluation of the potential effects of coalbed-methane production on the availability and sustainability of ground-water resources. This report presents preliminary results from an evaluation of the vertical separation between production intervals of coalbed-methane wells and nearby water-supply wells in the Raton Basin of Colorado.

Geographic information system software was used to estimate the vertical separation between production intervals of coalbed-methane wells and nearby water-supply wells, based on water-well construction data from the Colorado Division of Water Resources and gas-well construction data from the Colorado Oil and Gas Conservation Commission. In 2003, there were an estimated 1,370 water-supply wells in the Raton Basin in Colorado, and about 90 percent of these water-supply wells were less than 450 feet deep. The depths to the tops of the production (perforated) interval of 90 percent of the coalbed methane wells in the Raton Basin (for which data were available) are greater than about 675 feet. In most of the Raton Basin in Colorado and on the basis of estimated thickness of the vertical separation, the potential for interference of coalbed-methane wells with nearby water-supply wells likely is limited. In most areas, the production intervals of coalbed-methane wells and nearby water-supply wells are separated by hundreds to a few thousand feet of rock. Locally, the estimated vertical separation between production intervals of coalbed-methane and water-supply wells is less than 100 feet. It is assumed that in those areas, production by coalbed-methane wells has a greater potential for interfering with nearby water-supply wells. However, more detailed geologic and hydrologic information is needed to quantify the potential effects of coalbed-methane production on water levels and the availability and sustainability of ground-water resources.

References Cited

Abbott, P.O., Geldon, A.L., Cain, Doug, Hall, A.P., and Edelmann, Patrick, 1983, Hydrology of Area 61, Northern Great Plains and Rocky Mountain coal provinces, Colorado and New Mexico: U.S. Geological Survey Water-Resources Investigations Report 83–132, 99 p.

American Gas Association, 2006, How to measure natural gas: accessed March 15, 2006, at URL *http://www.aga.org/Content/NavigationMenu/About_Natural_Gas/How_to_Measure_Natural_Gas/How_to_Measure_Natural_Gas.htm*

Colorado Division of Water Resources, 2003, Well data: accessed September 26, 2003, at URL *http://water.state.co.us*

Colorado Division of Water Resources, 2005, Guide to Colorado well permits, water rights, and water administration: accessed October 4, 2005, at URL *http://www.water.state.co.us/pubs/wellpermitguide.pdf*

Colorado Oil and Gas Conservation Commission, 2000, Exploration & production (E&P) waste management: accessed December 15, 2005, at URL *http://www.oil-gas.state.co.us/RR_Asps/900Series.pdf*

Colorado Oil and Gas Conservation Commission, variously dated, Rules and policies (100-1100 series): accessed December 15, 2005, at URL *http://www.oil-gas.state.co.us/RR_Docs/CompleteRules.pdf*

Colorado Oil and Gas Conservation Commission, 2005, accessed March 28, 2005, at URL *http://www.oil-gas.state.co.us*

Flores, R.M., and Bader, L.R., 1999, A summary of Tertiary coal resources of the Raton Basin, Colorado and New Mexico, chap. SR of Fort Union Coal Assessment Team, 1999 Resource Assessment of Selected Tertiary Coal Beds and Zones in the Northern Rocky Mountain and Great Plains Region: U.S. Geological Survey Professional Paper 1625–A [accessed September 8, 2004, at *http://greenwood.cr.usgs.gov/energy/coal/PP1625A/Chapters/SR.pdf*].

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

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A., 2004, Estimated use of water in the United States in 2000: U.S. Geological Survey Circular 1268, 46 p.

Kuuskraa, V.A., and Brandenberg, C.F., 1989, Coalbed methane sparks a new energy industry: Oil and Gas Journal, v. 87, no. 41, p. 49–56.

Nuccio, V.F., 2000, Coalbed methane—potential and concerns: U.S. Geological Survey Fact Sheet FS–123–00, 2 p.

Schenk, C.J., Nuccio, V.F., Flores, R.M., Johnson, R.C., Roberts, S.B., and Collett, T.S., 2001, Coal-bed gas resources of the Rocky Mountain region: U.S. Geological Survey Fact Sheet FS–110–01, 2 p.

The Chemical Rubber Company, 1973, Handbook of chemistry and physics, 1973–1974, 54th ed.: Cleveland, Ohio, CRC Press, 2,406 p.

Theis, C.V., 1935, The relation between lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: American Geophysical Union Transactions, v. 16, p. 519–524.

Topper, Ralf, Spray, K.L., Bellis, W.H., Hamilton, J.L., and Barkmann, P.E., 2003, Ground water atlas of Colorado: Colorado Geological Survey Special Publication 53, 210 p.

U.S. Geological Survey, 2004, National elevation dataset: U.S. Geological Survey, accessed March 28, 2005, at URL *http://seamless.usgs.gov/*.

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