Potential Ground-Water Drawdown and Recovery from Coalbed Methane Development in the Powder River Basin, Montana

Project Completion Report to the U. S. Bureau of Land Management

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by

John Wheaton

John Metesh

Montana Bureau of Mines and Geology
Montana Tech of The University of Montana
1300 West Park Street
Butte, Montana 59701-8997

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Introduction

Natural gas (methane) production from coal beds is a new and potentially important industry in Montana. In parts of Montana, coal seams hold two valuable energy resources (coal and methane), plus ground water that is vital to a stable agricultural economy. Competition between interests in exploiting and utilizing these resources necessitates development of hydrologic impact predictions. Predictions of the potential impacts of coalbed methane (CBM) development can be based in a large part on the understanding of coal hydrogeology that has grown from monitoring programs, active during the past 30 years in southeastern Montana. While coal mining and CBM development affect ground-water systems in somewhat different ways, the data collected at monitoring wells and the interpretations of those data provide a sound scientific basis for discussions of CBM impacts.

Coalbed methane is generated by two mechanisms: 1) microbial activity (biogenic methane); and 2) thermal generation (thermogenic methane) (Rice, 1993, p. 160). Early biogenic processes produce methane during early burial and coalification by methyl fermentation and carbon dioxide reduction. Much of the early biogenic methane is lost to the atmosphere. In active ground-water flow systems, late-stage biogenic methane can be produced by reduction of carbon dioxide. With increasing depth of burial and higher temperatures, thermogenic methane is produced. Thermogenic generation produces large quantities of methane. Due to the depth of burial and presence of confining layers above coal seams, relatively little late biogenic or thermogenic methane is lost. In the United States, major development has focused on thermogenic coalbed methane. However, coalbed methane targeted by producers in the Powder River Basin is biogenic. The economic attractiveness of the Powder River Basin is based on large volumes of CBM at shallow depths. However, the volume derives not from the concentration of gas held in the coal, but rather from the large magnitude of the coal reserves.

The first documented use of CBM as an energy resource was in China, around the year 900 AD where it was transported in bamboo pipes and used to manufacture salt (Mavor and Nelson, 1997). The first known use in the United States was in the Powder River Basin during the early 1900's where CBM was captured from a water well and used for home heating (Mavor and Nelson, 1997). The realization that CBM represented a significant new energy resource for the nation occurred during mine safety work in Alabama (Pashin and Hinkle, 1997). Based on data published by the Potential Gas Committee (Pierce, 1999) coalbed methane (CBM) may represent about 15 percent of total natural gas resources in the United States. Production is well established in New Mexico, Colorado, Utah, Alabama, and Wyoming, and is expected to be developed in the Powder River Basin area of Montana over the next few years.

Although economic benefits to the Powder River Basin from CBM production appear promising, residents in the watersheds of Rosebud Creek, Tongue River and Powder River are concerned over potential impacts to surface-water and ground-water resources. Potential impacts include depletion of ground-water resources, and damage caused by release of water containing high sodium-adsorption ratios and other dissolved constituents to surface water bodies and soils. Coal seams are the major aquifers for local stock and domestic uses in southeastern Montana and support a variety of wildlife species. The coals are important targets for water-well drilling in the area because they are the most laterally continuous aquifer units with relatively high permeability and with water quality capable of sustaining traditional uses. The coalbeds sustain springs and provide ground-water baseflow to streams.

The purpose of the current report is to present an evaluation of potential ground-water impacts from the development of coalbed methane (CBM) in southeastern Montana. Ground-water issues include reduction in hydrostatic head in coal aquifers, quantities of produced water and disposal options, impacts to alluvial aquifers and ground-water recovery potential. The area of analysis is within the geologic feature referred to as the Powder River Basin (PRB) in southeastern Montana (Figure 1). Coal seams in this area are within the Paleocene, Tongue River Member of the Fort Union Formation. The coals are aquifers that provide water to a significant percentage of springs and wells in the area. Due to their status as aquifers, drawdown within these coal seams is an important consideration for development of CBM. In areas of Montana with CBM potential that are outside the Powder River Basin, the coal seams may not be aquifers and reduction in ground-water pressure may be less important. However, estimates of discharge rates from producing CBM wells are critical in any assessment of environmental effects from different disposal options. Some discussions and monitoring data of CBM impacts can be transferred to other areas, however, caution is urged. It is particularly important to note the differences between Wyoming and Montana, even within the Powder River Basin. Impact discussions from the Tertiary Fort Union Formation may be of only limited relevance to Cretaceous coals in Montana.

Generalized stratigraphy for the Powder River Basin, southeastern Montana.		
Wasatch Fm		
Fort Union Fm	Tongue River Mbr	Anderson Co Knobloch Co
	Lebo Mbr	
	Tullock Mbr	
Lance Fm		
Fox Hills Fm		

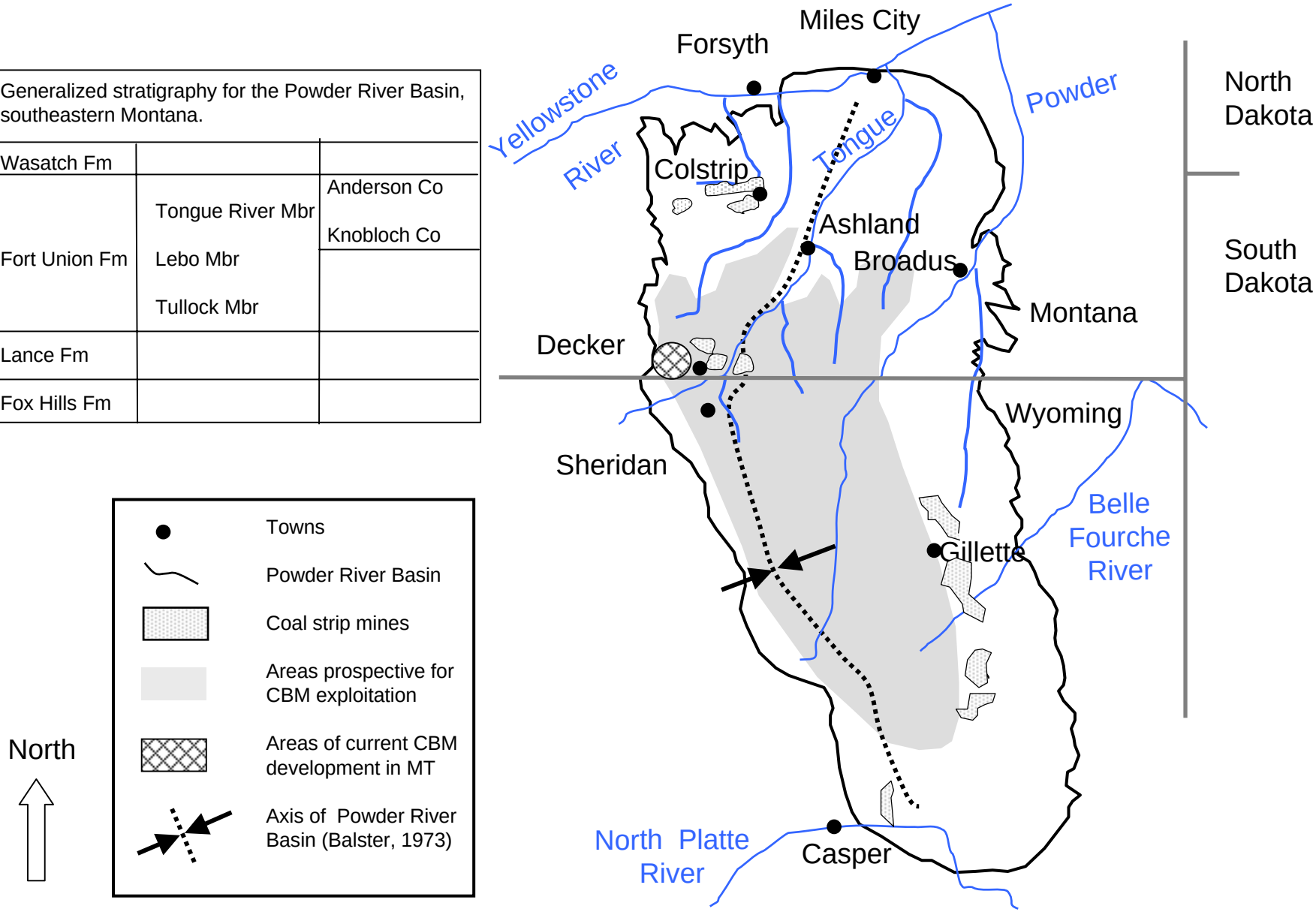


Figure 1. Roughly one-third of the Powder River Basin lies in Montana and two-thirds in Wyoming.

Data sources

Many hydrogeologic studies were completed during the coal assessment work of the 1970's and early 1980's. Many of these studies were funded by the United States Bureau of Land Management (U. S. BLM) and the work was carried out by U. S. BLM, U. S. Bureau of Reclamation, and Montana Bureau of Mines and Geology (MBMG) and the U. S. Geological Survey (USGS). Since then, the MBMG has maintained a continuous study of coal-strip-mine impacts to hydrogeologic systems in southeastern Montana, funded in large part by U. S. BLM and the State of Montana. In addition to publications, data have been retrieved from mine company permit applications on file with the State of Montana, Department of Environmental Quality, Industrial and Energy Minerals Bureau in Billings, Montana.

The available hydrogeologic data for the Powder River Basin provide an accurate description of the ground-water systems. Data for these areas provide aquifer characteristics for the coal seams and to a lesser degree for the shallow sandstone units. Hanging Woman Creek watershed, the object of modeling in this report, is particularly well described in several studies, including: Ground-water Subgroup of Water Work Group Northern Great Plains Research Program (1974); US Bureau of Land Management (1975, 1977); Delk and Waldhaus (1977); Slagle and others (1983); McClymonds (1984, 1986); Daddow (1986); and Cannon (1989); and, Van Voast and Thale (2001). Data include aquifer test results, water-level measurements and lithologic descriptions. The data from the coal studies are generally limited to those portions of the coal fields with less than about 200 feet of overburden, since the purpose was to identify hydrologic conditions where strip mining could be economically feasible.

Mine company reports and permits contain hydrogeologic data. The description of aquifer characteristics in this report includes aquifer test results from the following company reports: Beartooth Coal Company (1980); Consolidated Coal Co. (1981); Decker Coal Co. (2000); Meridian Minerals Co. (1992); MONTCO Mine (1983); Peabody Coal Company (1986); Spring Creek Coal Co. (1996); Western Energy Co. (1989); Westmoreland Resources Co. (1998); and Wolf Mountain Mine (1982).

To provide a source of information on CBM activities and natural resource publications, the Montana Bureau of Mines and Geology (MBMG) and the Bureau of Land Management have jointly created a searchable, annotated bibliography on an Internet-web page. Readers interested in finding additional information on subjects relating to the Powder River Basin or coalbed methane are encouraged to visit this site accessible through the MBMG home page at http://mbmg/mtech/edu. The MBMG has published a geologic map showing areas of likely CBM development in southeastern Montana (Van Voast and Thale, 2001). A water-resources map showing the locations of springs and wells in the PRB area is available (Kennelly and Donato, 2002).

Regional hydrogeologic setting

Coalbed methane development in Montana is currently concentrated in the Decker area, on the western edge of the Powder River Basin (Figure 1). Paleocene sandstone, shale and sub-bituminous coal of the Tongue River Member of the Fort Union Formation underlie the region. Coal seams of the Tongue River Member split and converge due to the depositional processes (Flores and Bader, 1999), creating a complex stratigraphic package of interbedded aquifers and aquitards.

Total coal resources in the Powder River Basin are estimated at 1.3 trillion tons (Rightmire and others, 1984). Of the numerous coalbeds, the primary targets for CBM development in Montana are the Anderson, Dietz (WYODAK in Wyoming), Canyon, Wall and Knobloch.

Ground water as a resource

Southeastern Montana is a sparsely populated, semi-arid grassland region with rolling to ruggedly dissected topography. The area is semi-arid, receiving less than 15 inches of precipitation per year in most places. Most of the land is utilized for cattle ranching, dryland farming, or coal mining with flood-irrigated farmlands along stream valley floors. Water for irrigation comes from several surface-water sources**,** especially from the Tongue River.

Domestic and livestock water supplies are dependent on ground-water resources. Wells penetrate alluvium in valley bottoms, and sandstone and coalbeds throughout the area. Water wells are typically less than about 300 feet deep. The Montana Ground-Water Information Center (GWIC) lists 4,520 wells within the 5,321 square-mile area of the Tongue River Member in the Powder River Basin that lies within Montana. This is an average density of 1 well per 1.2 square miles (MBMG file data). Spring data for this same area indicate an average density of at least 1 spring per 5 square miles (Kennelly and Donato, 2002). Preliminary data from the U. S. Forest Service indicate springs densities far higher than this number, particularly on Forest land.

Water-supply well locations tend to be concentrated within 2 to 4 miles of the major coal outcrops (Kennelly and Donato, 2002). Drilling depths to coal seams are least in these areas, providing good targets for water development. Springs occur throughout the Basin, but geologic contacts with less-permeable units at the base of clinker zones and areas of coal outcrops support most of them.

Aquifer physical characteristics

Coal seams are important aquifers in southeastern Montana. Coal seams are more laterally continuous than sandstone units in the Tongue River Member, one example of which is shown in McClymonds (1984a). The formation of valleys by the northward-flowing Rosebud Creek, Tongue River, Powder River and their tributaries have created considerable topographic relief. Coal seams crop out along the valley walls and subcrop beneath valley fill and surface water bodies. It is the ability to transmit water, the extensive nature of the coal seams, and their superior water quality that make them the targets for stock and domestic well drilling, while the outcrop exposures provide springs for livestock and wildlife, and baseflow to rivers.

The amount of water that an aquifer will yield to a well is dependent on four physical characteristics of the aquifer: hydrostatic pressure, hydraulic conductivity, saturated thickness, and storativity. The hydrostatic pressure (measured as water level or head) provides the energy to force the water through the aquifer to maintain flow to a well. Without hydrostatic pressure, little or no water will flow toward a well to replace water removed by pumping and production will decrease. Hydrostatic pressure is the aquifer characteristic that is most susceptible to outside influences, and is the one most likely to be impacted by CBM activities.

Hydraulic conductivity is the ease with which water moves through the geologic material. Pore size and interconnectedness control hydraulic conductivity. External activities, such as CBM production, typically have little or no affect on hydraulic conductivity.

The saturated thickness of the aquifer is that portion through which water flows. In an unconfined (water table) aquifer the hydrostatic pressure is equal to the saturated thickness times the pressure exerted per foot of water (0.433 pounds per square foot per foot of water height). However, most domestic and livestock wells withdraw water from confined aquifers, and the hydrostatic pressure is greater than the saturated thickness, being a function of the height of water in a well open to the aquifer. Some impacts, such as surface-coal mining, reduce the saturated thicknesses of aquifers adjacent to the mines due to the de-watering that results from gravity drainage to the mine pits. Producers of CBM reduce the water pressure, but report that actual de-watering is not desirable. Therefore, reduction in saturated thickness is not expected as a result of CBM development, except in those situations where reduction in hydrostatic pressure extends to unconfined portions of aquifers.

Storativity describes the quantity of water released from a unit area of an aquifer due to a unit reduction in hydrostatic pressure. In a water table, or unconfined aquifer, storativity values of 0.1 or 0.2 are not uncommon. Given a storativity value of 10^{-1}, 0.1 ft^3 of water would be released in response to a 1 foot drop in head from each 1-ft^2 area of the aquifer due to gravity drainage. In confined aquifers, the aquifer is not being de-watered by drainage due to production, but rather water is being released by expansion

of the aquifer material and pore water. Storativity values of 10^{-4} or 10^{-5} are common. In the case where storativity is equal to 10^{-4}, each 1-ft decrease in head will release 10^{-4} ft^3 of water from each 1-ft^2 area of the aquifer. Storativity values of coalbeds are within the range of the preceding example for a confined aquifer. For this reason, removing fairly small amounts of the total water held in the aquifers can cause large reductions in hydrostatic pressure and thereby can greatly reduce the water that can be produced at wells and springs. In those areas where the reductions in pressure are great enough, ground-water flow to wells and springs will be reduced. Storativity of the aquifers is not expected to be impacted by external activities, such as CBM production, unless confined aquifers are de-watered to the point of becoming unconfined.

Coal in this area has hydraulic conductivity values that are similar to but higher than overburden and under burden sandstone (Table 1 and Figure 2). Basin-wide, aquifer tests of sandstone units have a geometric-mean hydraulic conductivity of 1.8×10^{-1} ft/day, with a standard deviation of approximately 1 order of magnitude. Test results from coal units indicate a geometric-mean value of 1.1 ft/day, with a standard deviation of 1 order of magnitude. Storativity values for tests in confined portions of the aquifers average 5×10^{-4} for sandstone and 9×10^{-4} for coal.

Ground-water flow

Recharge to the ground-water systems occurs along clinker-capped ridges, and in up-dip areas of outcrops of sandstone and coal units, especially where streams cross these outcrops. Ground water flows through sandstone and coal aquifers from topographically high recharge areas to low areas along major stream and river valleys. In the Decker area of Montana, ground-water flow is eastward from the Wolf Mountains toward the Tongue River and northward toward the Yellowstone River. East of the Hanging Woman Creek focus area ground-water flows from Wyoming toward the north.

Ground-water flow in coal seams occurs primarily along cleat faces. Face cleat is more continuous than butt cleat, is the dominant cleat set, and is oriented parallel to the direction of bedding dip. Butt cleat is less dominant and oriented parallel to the direction of bedding strike. Anisotropic hydraulic conductivity can be expected in the coal due to the development of cleat. The direction of maximum hydraulic conductivity will parallel the direction of face cleat and the direction of minimum hydraulic conductivity will parallel butt cleat (Stone and Snoeberger, 1977). In the Powder River Basin in Montana, the expected direction of maximum hydraulic conductivity can be inferred from regional dip directions shown for Upper Cretaceous units by Balster (1973). In the Decker area the direction of maximum hydraulic conductivity is most likely northwest-southeast (perpendicular to regional strike) with secondary hydraulic conductivity oriented northeast-southwest (Davis, 1984). In the area of Hanging Woman Creek the direction of maximum hydraulic conductivity should be oriented

Table 1. Aquifer test results for alluvium and for Fort Union Formation aquifers in southeastern Montana indicate that alluvium, sandstone and coal are all potential water resources.

	Location (number of tests) *	Hydraulic conductivity (ft/day)			Storativity (unconfined) Mean	or	Storativity (confined) Mean
		- 1 Std Dev	Geometric Mean	- 1 Std Dev			
Alluvium							
	PRB Wide (206)	1.1E+01	6.1E+01	3.3E+02	8.E-02		
	Hanging Woman Basin (21)	2.3E+00	2.8E+01	3.4E+02	2.E-03		
Sandstone							
	PRB Wide (54)	1.5E-02	1.8E-01	2.1E+00			5.E-04
	Hanging Woman Basin (11)	1.3E-01	4.2E-01	1.4E+00			ND
Coal							
	PRB Wide (370)	9.8E-02	1.1E+00	1.3E+01			9.E-04
	Hanging Woman Basin (88)	4.3E-02	4.3E-01	4.3E+00			3.E-04

* PRB refers to tests within the entire Powder River Basin, Montana.
The numbers in parentheses show the number of tests for which hydraulic conductivity was calculated.
Hanging Woman Basin refers only to tests for the area included in the ground-water model.
ND: No Data

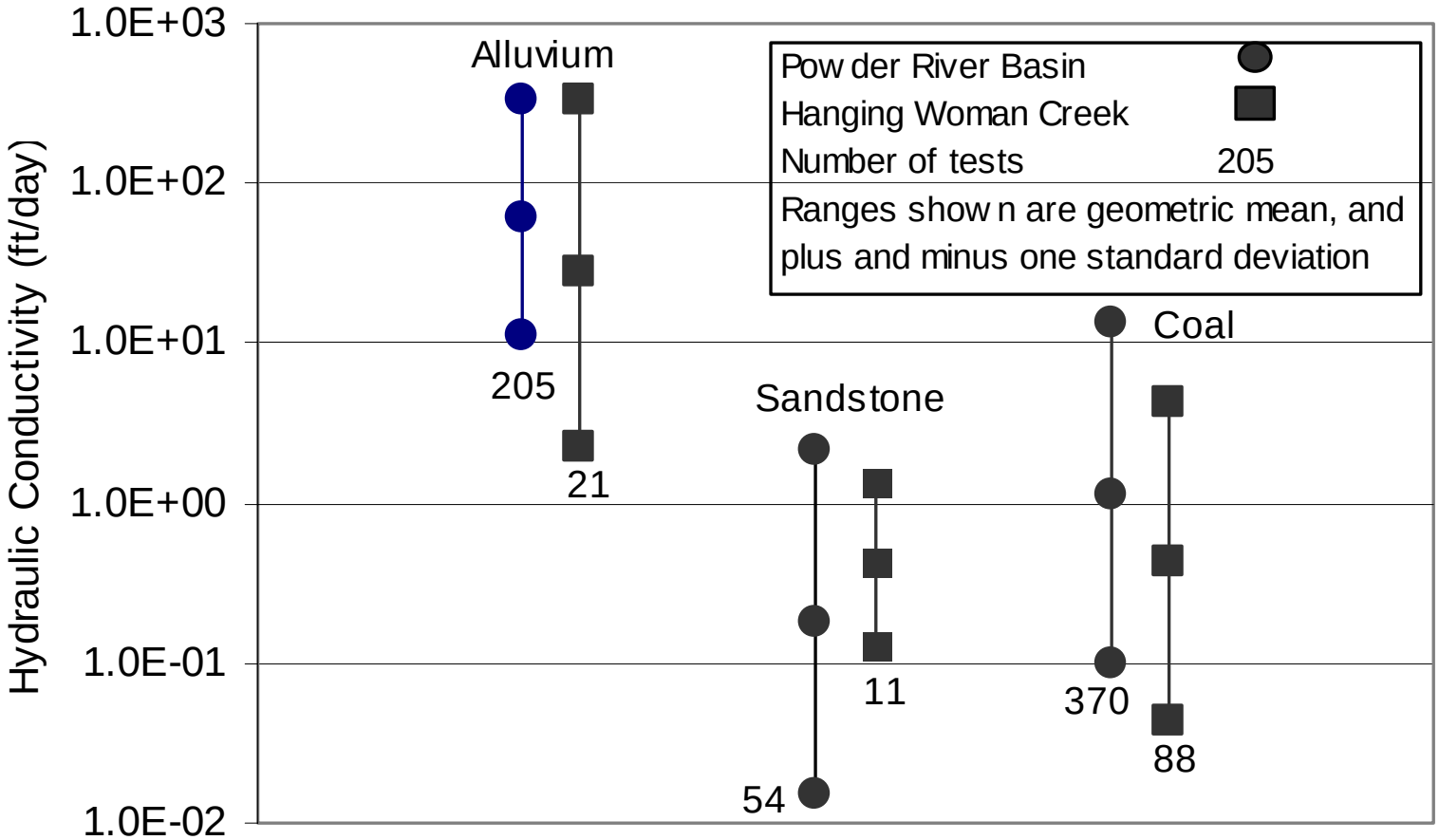


Figure 2. Published hydraulic conductivity values for aquifers in the Hanging Woman Creek area are typical for values reported for the entire Powder River Basin.

north-south, becoming northeast-southwest in the Otter Creek area, and east-west in the Little Powder River area. The ratio of anisotropy at three at three test sites was determined to be 0.3 to 1, 0.4 to 1, and 0.6 to 1 (Stone and Snoeberger, 1977), (Stoner, 1981).

Faults can also have a strong influence on the direction of ground-water flow. In the Decker area, faults have been shown to be barriers to ground-water flow (Van Voast and Reiten, 1988).

Evolution of ground-water quality

In the Montana portion of the Powder River Basin, changes in ground-water quality proceed along a known and predictable reaction path (Davis, 1984), (Van Voast and Reiten, 1988), (Clark, 1995). Water quality can be described in terms of the dominant species of cations and anions, calculated as a percentage of the total reacting species (equivalents of solute per liter of water). Slightly acidic precipitation falls in recharge areas and dissolves available carbonate salts of calcium (Ca^{+2}) and magnesium (Mg^{+2}) (calcite, dolomite). Near recharge areas, oxygen carried by the water reacts with sulfide minerals (pyrite and marcasite) producing sulfate, which with sodium (Na^{+1}), calcium (Ca^{+2}) and magnesium (Mg^{+2}) add significantly to the total dissolved solids (TDS) load carried by the water. Further along the flow path, cation exchange with sodic shales increases the proportion of sodium (Na^{+1}), decreases calcium and magnesium concentrations, and increases TDS. Consequently, ground-water from coal seams may have sodium-adsorption ratio (SAR) values that exceed 40, and in some wells exceed 50 (Van Voast and Hedges, 1975). Deeper anaerobic conditions in the coal promote sulfate reduction by bacteria, resulting in a sodium-bicarbonate dominated water. The effect on the TDS of the water due to this series of reactions is shown on Figure 3. Specific conductance, or the ability of the water to transmit electricity, is proportional to TDS.

The concentration of total dissolved solids (TDS) in the water reflects a sum of all constituents. Ground-water quality is a function of chemical reactions between the water, constituents in the water, and the surrounding geologic material. Produced water is unlikely to effect ground-water quality within producing areas of coal seams. Depending on water-disposal methods, ground-water quality in receiving areas may be impacted.

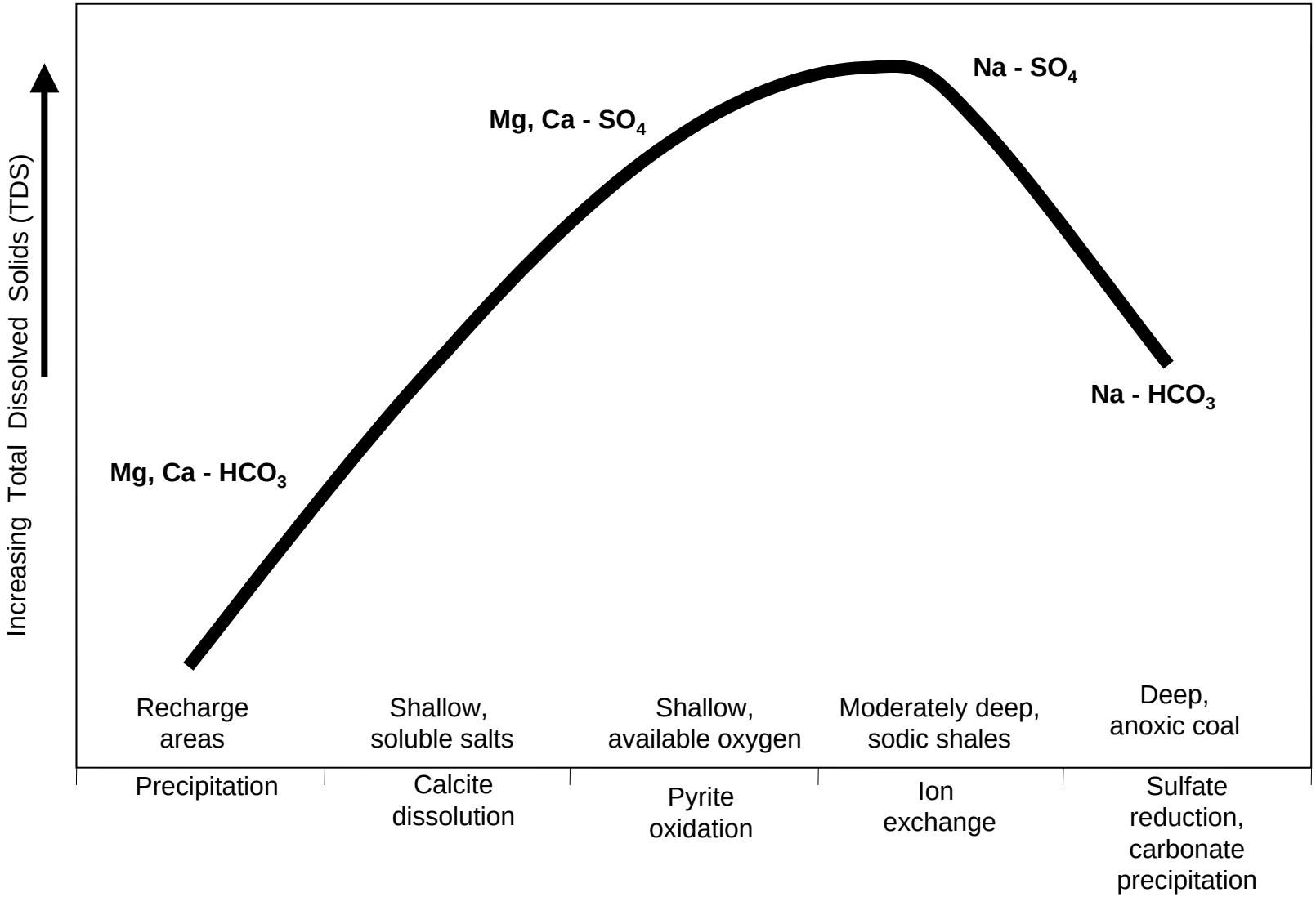


Figure 3. Dissolved-solids concentrations initially increase and then decrease along ground-water flow paths in the Fort Union Formation aquifers.

Overview of coalbed methane development and anticipated impacts

Site description and gas-production description

Methane is held on cleat surfaces and in micro-pores in coal (Rice,1993; Rightmire, and others, 1984). The gas is held in place by weak attractive forces between the coal and the gas and by hydrostatic pressure of ground water in the coal. To produce the gas, water is pumped from wells completed in the coal, reducing the hydrostatic pressure and allowing the gas to desorb. The gas and water move to the well as a two-phase fluid. The water enters the pump and is discharged through the water line. The gas flows up the well casing and is removed through gas lines to a low-pressure compressor.

Additional efficiency in reducing water pressure in the coalbeds is achieved by completing wells in grid patterns called pods. Pods typically cover an area of about 800 acres and consists of 10 to 15 wells completed in each coal seam, or one CBM well per 80 acres per producing coal seam. In some areas, as many as four coal seams are targeted, and pods may consist of as many as 40 or 50 wells. A central, low pressure compressor receives gas produced from the wells and advances the gas to a high-pressure compressor station that receives gas from several pods, moving the gas into pipelines for delivery to market.

The initial CBM development in Montana and Wyoming occurred adjacent to coal mines, where the hydrostatic pressure in the aquifers had been partially reduced by mine dewatering. Near Decker, Montana, CBM wells are being installed south and west of coal mines where the Anderson-Dietz coals are being mined. These coals, plus the deeper Canyon, Cook and Wall coals are prospective for CBM. In Montana, target coalbeds are generally 400 to 1000 feet below ground surface, deep enough for sufficient hydrostatic pressure to retain methane gas.

Anticipated hydrologic impacts from coalbed methane development

Hydrologic concerns over CBM production include depletion of ground-water resources for the duration of production plus recovery time, and impacts due to disposal of produced water.

Depletion of ground-water resources

Water levels in aquifers will be lowered for the duration of production from the well fields and may require decades to recover. During periods of production and recovery, water availability at some springs and wells will be reduced. Ground-water discharge provides baseflow to support perennial streams and during CBM production and aquifer recovery, stream flows may decline to less than present levels due to the reduction of ground-water base flow. During CBM production disposal of produced water will increase surface-water availability in some areas.

Compared to the receiving streams, the ground water produced with CBM typically contains higher concentrations of sodium and bicarbonate, and may also carry elevated concentrations of other constituents, including iron, fluoride, boron and ammonia. Sodium and specific conductance are of particular concern to downstream irrigators.

Large-scale surface coal mining, such as that at Colstrip and Decker, Montana, causes water-level responses that may approximate CBM development. Coal mines depressurize adjacent coal seams and, by gravity drainage at pit faces, they dewater them. Ground-water levels have been measured at wells in and adjacent to coal-strip mines near Decker for 30 years by Montana Bureau of Mines and Geology and by mining companies. Coalbed methane development has begun in Montana in an area where some of these monitoring wells are located (Figure 4). The West Decker Mine covers an area of about 4 square miles, and after 30 years of mining, 10 feet of drawdown were recorded at a distance of about 5 miles from the mine (MBMG file data). Drawdown at the East Decker mine is similar. Hydrographs of this effect are shown in figures 5 and 6. After coal is removed, the mining companies reclaim the sites, and the water levels tend to recover towards pre-mining levels. One example (Figure 7) shows drawdown due to mining at a distance of less than ½ mile, 15 years of depressed water levels, and recovery within about 3 to 4 years after reclamation. This site is near a recharge area and shows responses related to a coal mine that disturbed less than 5 acres. The mirror image of the drawdown and recovery limbs of this hydrograph demonstrate one example of the response to a long-term disturbance, although this ideal response cannot be expected in all cases.

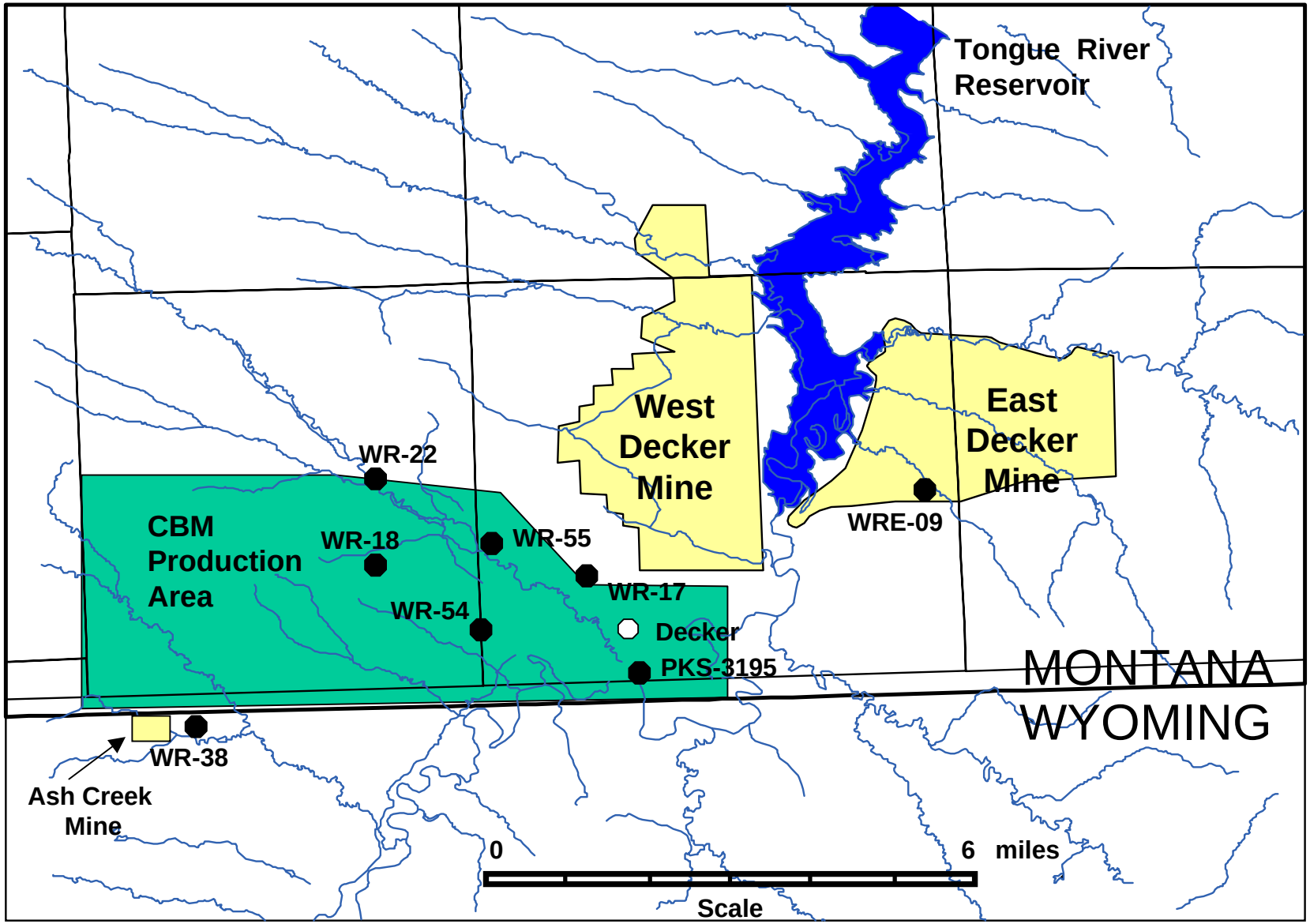


Figure 4. The ground-water monitoring program near the Decker mines has been maintained for nearly 30 years. Selected wells are shown in this figure.

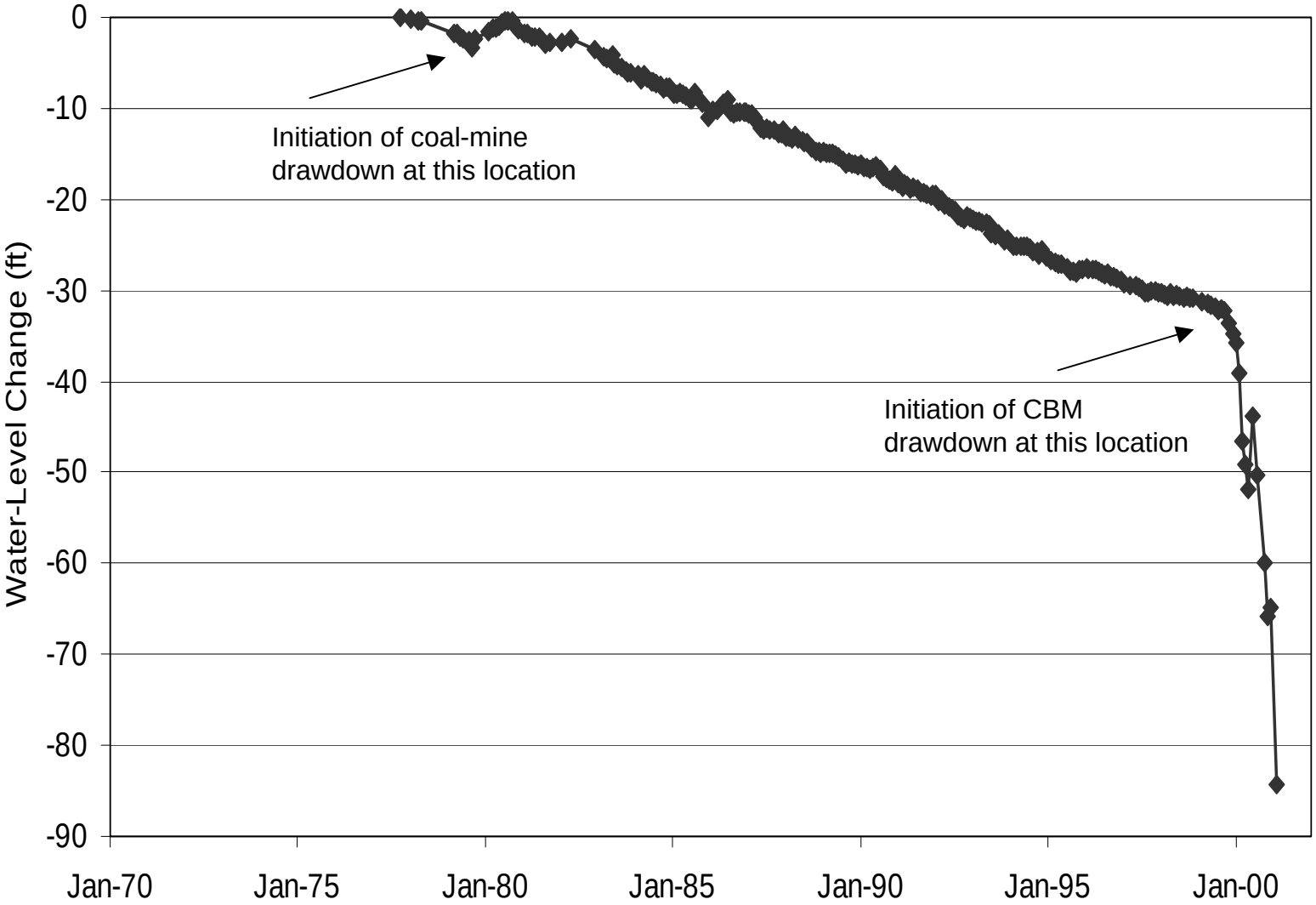


Figure 5. Water levels in the combined Anderson/Dietz coal at well WR-55 (Figure 4) have responded to coal-strip mining and to coalbed methane development.

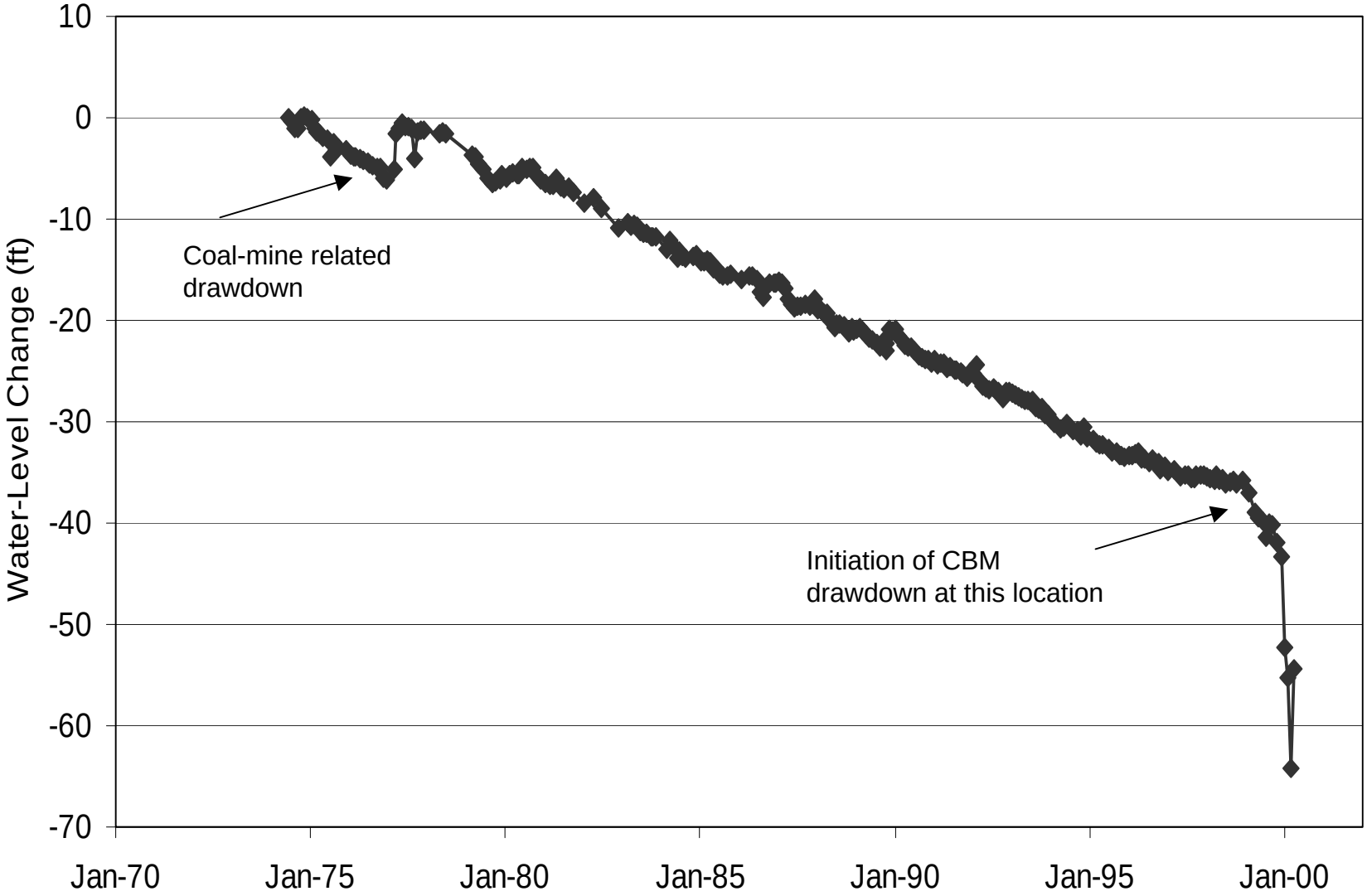


Figure 6. Water levels in the combined Anderson/Dietz coal at well WR-17 (Figure 4) have responded to coal-strip mining and coalbed methane development.

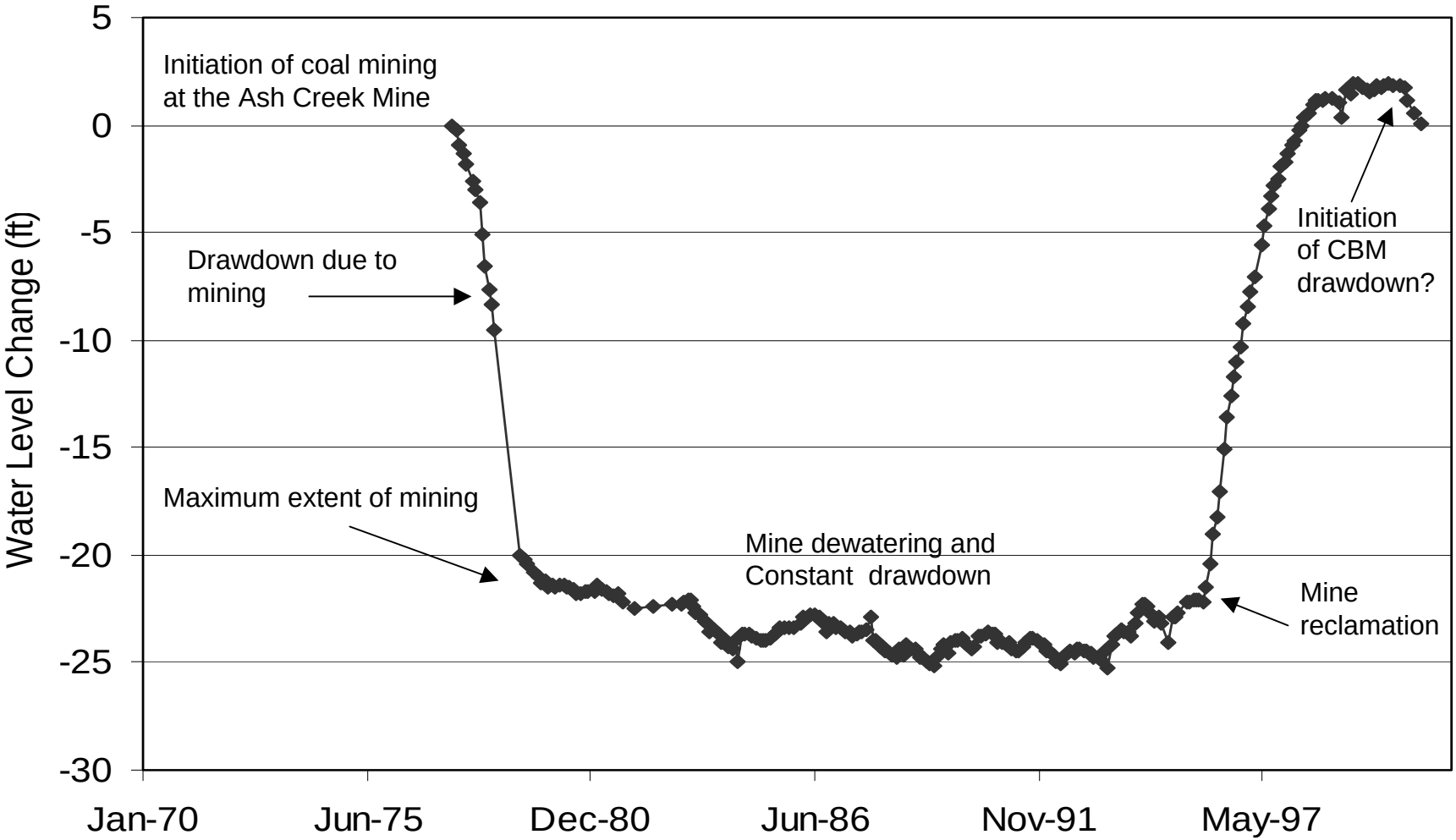


Figure 7. Water levels in the Anderson-Dietz coal at well WR-38 (Figure 4), less than ½-mile from the Ash Creek coal mine, recovered within 3 to 4 years after reclamation was completed.

Both the coal-mine and CBM-related drawdowns near the West Decker Mine are shown on Figure 8. Influences of CBM withdrawals have been marked by rapid water-level drops in comparison to the mine-induced drawdown (figures 5 and 6). In the first 1½ years of production, 10-feet of drawdown has extended as far as a 1- to 2-mile radius outside the CBM production field near Decker (Figure 8). As additional wells come on line and with continued pumping, the area of influence will expand. Water levels within the production field are drawn down to almost the tops of the coal seams.

The 2000 Annual Report of all coal mines in Wyoming indicates mine-induced drawdown reaching several miles from mines, and the drawdown due to CBM production exceeding that caused by surface coal mines (Hydro-Engineering, LLC, 2000). A review of data from Wyoming in the WYODAK coalbed methane Draft Environmental Impact Statement (EIS) indicates 5 feet of drawdown around existing coal mines after 15 years of mining at distances ranging from about 2 to 14 miles (U. S. BLM, 1999). Ground-water modeling of CBM impacts for that EIS predicted 5 feet of drawdown at distances of 10 to 22 miles from the edge of dense CBM development. In the 2002 Oil and Gas EIS for the Wyoming portion of the Powder River Basin, drawdown from Wyoming CBM development is projected to reach 100 ft in coal aquifers 3 miles into Montana, about 18 miles from CBM wells in Wyoming (U. S. BLM, 2002).

The purpose of removing water during CBM production is to lower the hydrostatic pressures to levels near the tops of the respective coal seams, thereby allowing methane to desorb from the coal. Monitoring water levels in producing coal seams within the production field is of little or no regional value. At best, data from within the field can only determine if the target drawdown is being met, which is a production issue rather than an impact issue. Coal-seam water-level monitoring near CBM production is complicated by violent degassing and foaming that can occur in monitoring wells. Consequently, once degassing has started in a monitor well, true water levels are difficult to measure. Several coal-mine monitoring wells have been abandoned due to degassing problems. Water-level monitoring wells for regional impacts in coal seams should be located outside producing fields. Monitoring water levels in sandstone units above and below a producing seam, adjacent to and within a producing field can provide valuable information on the rates and extent of vertical leakage between adjacent aquifers.

Disposal of produced water

The second issue associated with removing water from coal seams is the potential impact due to release of the water. Water with high SAR and specific conductance (SC) values can damage soils and may be toxic to plants. (Hanson and others, 1999). Water discharged from CBM wells is dominated by sodium and bicarbonate ions, with SAR values frequently greater than 40. Disposal options being considered for this water include land application, direct discharge to drainages or

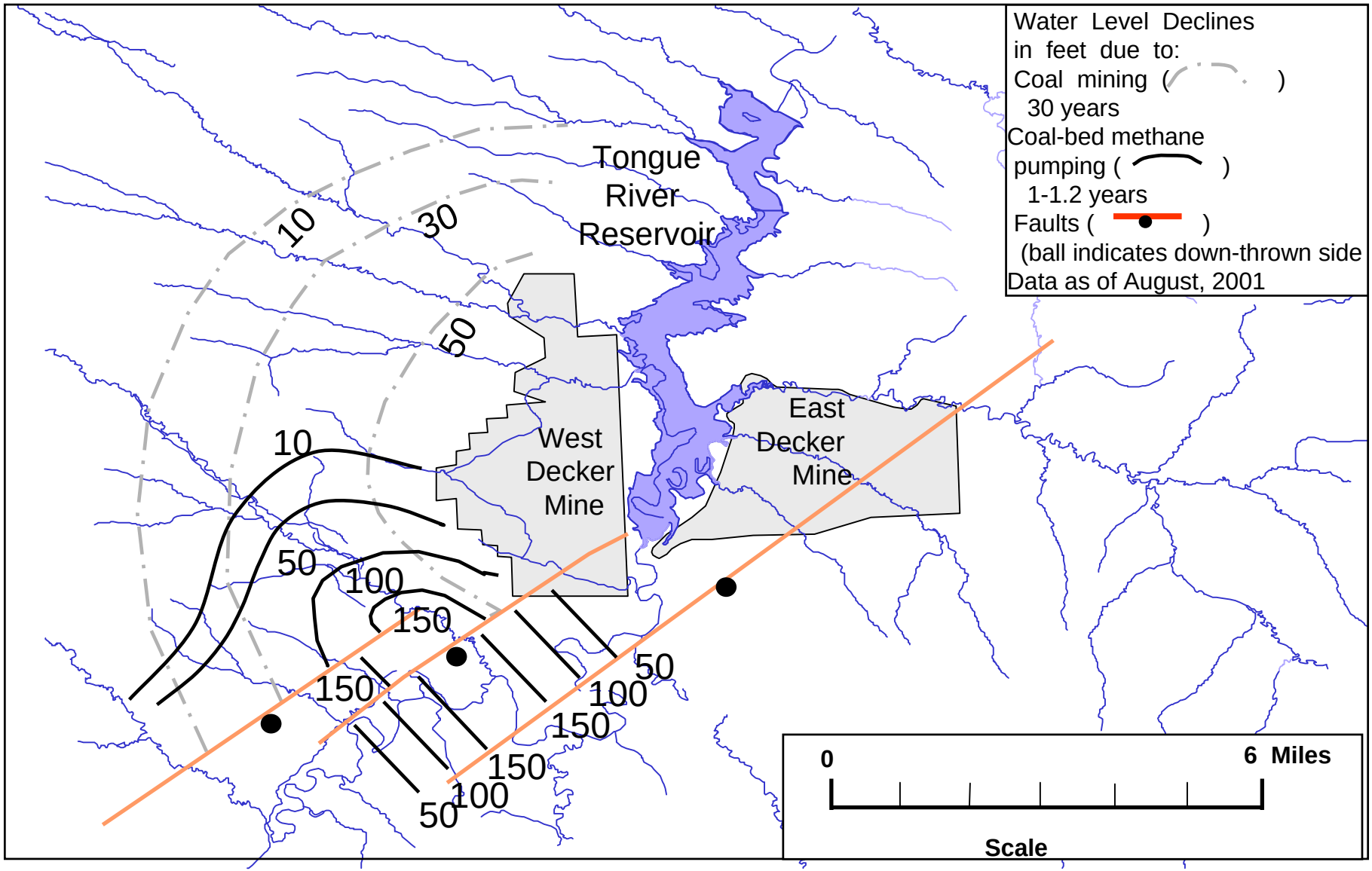


Figure 8. Changes in ground-water levels in the Anderson/Dietz coal zone have occurred due to coal-strip mining and coalbed methane development near the Decker mines.

rivers, storage in impoundments, or injection. To date, discharge to rivers and impoundments has been the default alternative in Montana.

Ground-water quality and estimates of ground-water discharge rates are information that is necessary in order to evaluate potential impacts from produced-water disposal. The preceding discussion of potential ground-water impacts due to aquifer drawdown, CBM-water production rates and potential impacts of produced-water disposal options is based on the interpretations of data collected near coal mines and throughout the Powder River Basin. The same data can be further used in computer flow models of the ground-water flow systems to provide an additional analysis of potential CBM impacts.

Computer modeling of potential impacts of coalbed methane development

Coalbed methane production is relatively new in Montana; large-scale production began in late 1999. The effects of long-term, sustained well-yields over areas of coalbeds that may exceed townships in size is undocumented in the State. Computer-generated flow modeling was applied to the CBM issue to demonstrate potential drawdown, discharge rates and recovery. The MODFLOW program (McDonald and Harbaugh, 1988) and a pre/post processor, Ground Water Vistas (Rumbaugh and Rumbaugh, 1998) were used here to develop a 3-dimensional ground-water flow model of the Hanging Woman Creek area. The model described herein is not meant to be predictive of drawdown or impacts in a specific area, but incorporates enough complexity to estimate typical field conditions and to demonstrate the various responses to pumping that can be expected throughout the basin. There are no data to support any chosen producing life for CBM wells. For the purpose of this evaluation, a life-of-well duration of 20 years was assumed.

Hanging Woman Creek originates in Wyoming and flows north into the Tongue River near Birney, Montana. Rocks underlying the area include sandstone, siltstone, shale, and coal of the Tongue River Member of the Fort Union Formation of Paleocene age. The Eocene Wasatch Formation crops out in the highest ridges of the area and is of limited areal extent within the study area. The Hanging Woman Creek area was chosen for both its simplicity and complexity, and for the existing hydrologic data. Results of several hydrologic studies in this area have been published. Hydrologic characteristics for this area are similar to other areas of the Powder River Basin (Figure 2). The area is considered a prime target for CBM production, however there are no impacts in this area to date either from CBM or coal mining. There are at least three roughly parallel coalbeds capable of producing methane dipping at a nearly uniform gradient of 0.004 toward the southwest. Coalbeds are separated by as much as 150 feet of interburden sandstones and claystones. The outcrop of the uppermost coalbed is bounded by a perennial stream on the west and an intermittent stream on the east. Several normal faults have been mapped by Culbertson and others (1978), and Culbertson and Klett (1979a and 1979b); fault offset ranges from a few feet to more than 200 feet. Many of the faults have displacements greater than the thickness of the coalbeds (about 30 feet) and thus, may form hydrologic barriers as noted in the Decker area by Van Voast and Reiten (1988). Several studies provide descriptions of the hydrogeology in this area, including VanDerwalker (1975), Ground-water Subgroup (1974), U. S. BLM (1975), Delk and Waldhaus (1977), McClymonds, (1986), and Cannon (1989). Although limited to small study subareas, these reports provide data for hydraulic conductivity and storage coefficients of the upper coalbeds and the alluvium associated with streams. The modeled area covers all or parts of T8S R43E, T8S R44E, T8S 45E, T9S 43E, T9S 44E, and T9S 45E in southeastern Montana near the Wyoming Border (Figures 9 and 10).

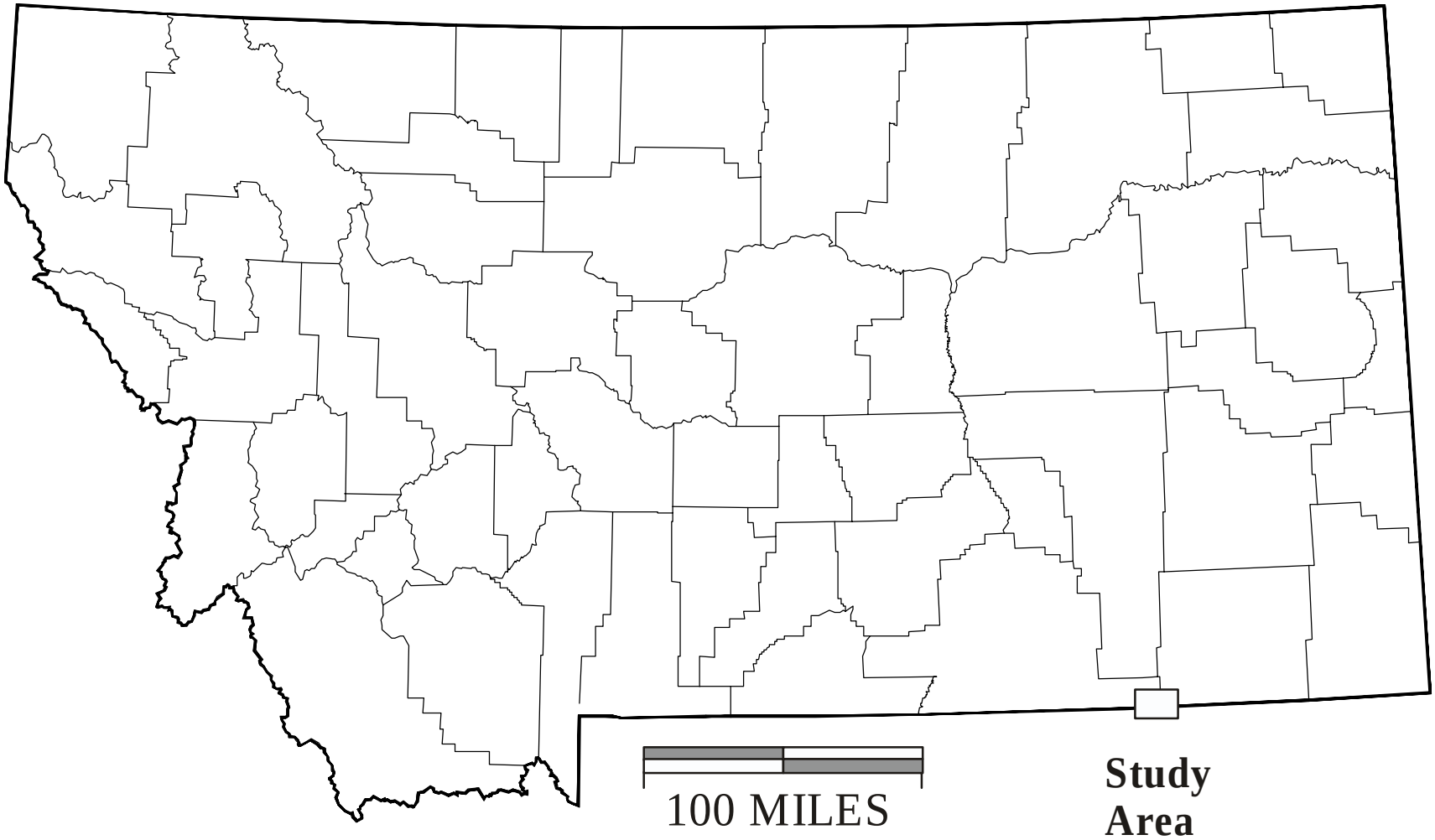


Figure 9. The model area includes parts of Big Horn and Powder River Counties in southeast Montana and Sheridan County in Wyoming.

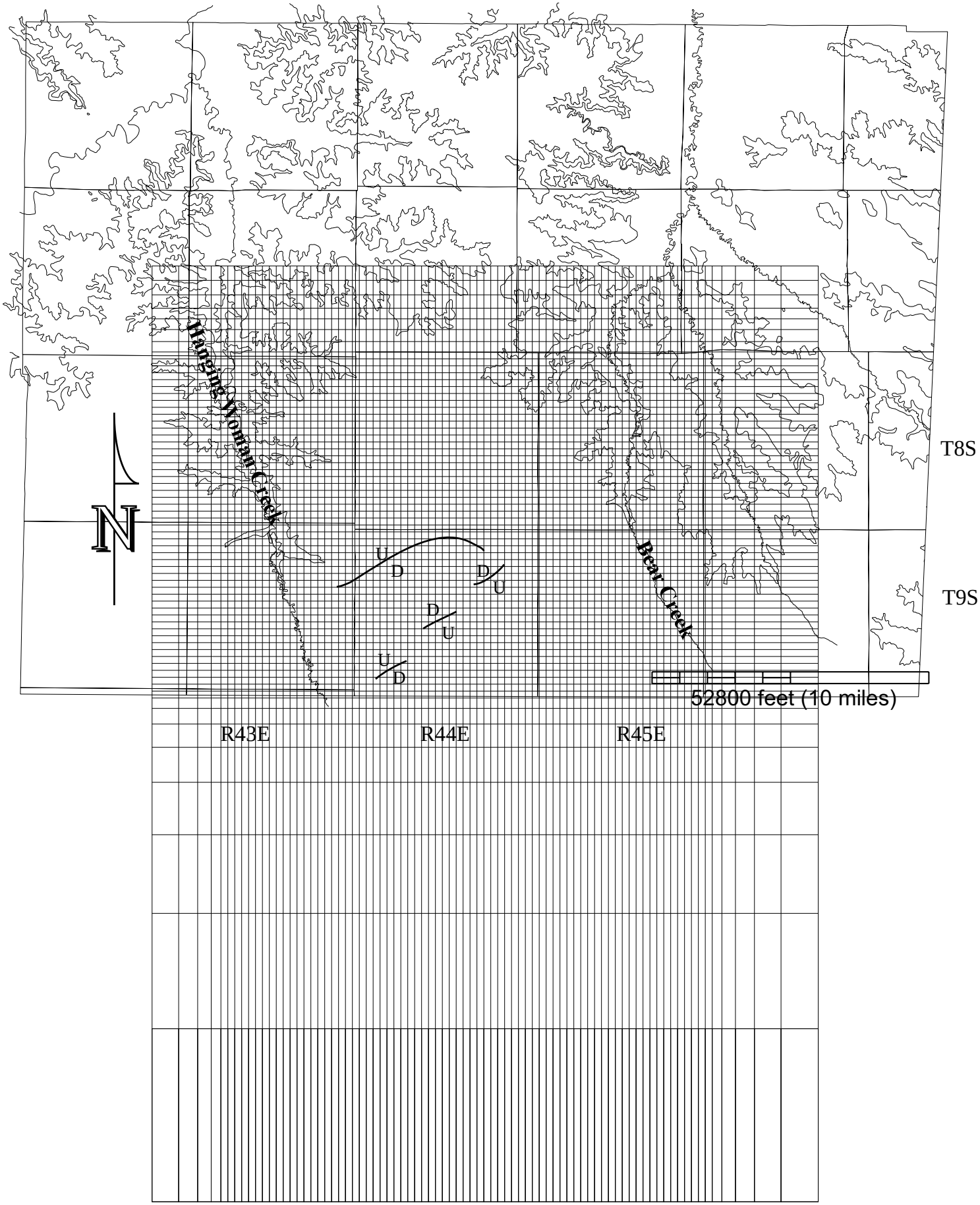


Figure 10. The grid spacing for the model is 1320 feet square in the central area of the model and increases to a maximum of 33,000 feet on the south edge. The Anderson coal outcrop and the larger faults mapped by Culbertson (1979a) are shown.

Model dimensions

The model area includes Bear Creek on the east and Hanging Woman Creek on the west (Figure 10). The uppermost CBM target, the Anderson coalbed, crops out in both drainages. The northern boundary of the model is the approximate middle of T7S, and the southern boundary is 18-miles south of the Montana - Wyoming state line. The north and south boundaries were not based on hydrologic features, but rather are intended to be sufficient distance from the area of interest to reduce “edge effects” in the model.

Bear Creek and Hanging Woman Creek were simulated using the MODFLOW river package. Stream beds were modeled in the top layer and their positions and elevations were based on 1:24,000-scale topology. Stream-bed conductance, which is a function of hydraulic conductivity and bed thickness, was based on the hydraulic conductivity of the alluvium.

The model grid was set up for 40-acre spacing in the central area to allow 80-acre well spacing commonly used in coalbed methane development. The model consists of 65 rows and 80 columns. The grid spacing was 1,320 feet for columns and rows in the central area of the model; the spacing was increased toward the edges of the model for a maximum column width of 7,100 feet and a maximum row width of 33,000 feet (Figure 10). Six layers were used to simulate the three principle coalbeds, the overburden and stream beds, and the interburden between coalbeds. The elevation and thickness of each layer was based on isopach maps presented by Culbertson and Klett (1979a and 1979b); layers were offset to reflect the larger faults in the central area of the model (Figure 10). The final version of the model consisted of 31,200 active cells.

Each of the six layers of the model represents a hydrostratigraphic unit, either clastics or coal (Table 2). Aquifer parameters used in the model were based on those reported by the U.S.BLM (1977b) and fall well within the reported range for similar lithologies found in other areas of southeast Montana (Table 1). The interburden units consist of interbedded sandstone and claystone layers. Aquifer tests probably targeted sandstone layers; for the purposes of this model, the interburden units are lumped and assigned a single set of aquifer parameters.

Table 2. Modeled hydrostratigraphic units are represented by six modeled layers (data from U. S. BLM, 1977b)

.

Layer	Lithology	Horizontal hydraulic conductivity (feet/day)	Average thickness (feet)	Available head * (feet)	Storage coefficient
1	overburden (sandstone and claystone)	5	200	2 to 150	1E-01
	stream bed (gravel and sand)	88	1	stream stage	N/A
2	Anderson coalbed	3	30	50 to 450	6E-05
3	interburden (sandstone and claystone)	0.1	250	150 to 450	1E-04
4	Canyon coalbed	1.5	20	200 to 450	6E-05
5	interburden (sandstone and claystone)	0.1	150	400 to 600	1E-04
6	Wall coalbed	2	10	350 to 600	6E-05

*head in each unit varies and depends on geologic and hydrogeologic conditions; values are typical for the central area of the model.

No data were available for horizontal anisotropy nor for vertical hydraulic conductivity for any of the hydrostratigraphic units. Horizontal hydraulic conductivity was assumed to be isotropic ($K_x = K_y$) for the model. The lithology of the overburden and interburden layers suggest a much lower vertical hydraulic conductivity (K_v) and were assumed to be 1% of the value used for the horizontal hydraulic conductivity. The vertical hydraulic conductivity of the alluvium and coal beds were assumed to be 10% of the horizontal hydraulic conductivity.

Calibration

Calibration most often involves comparing modeled head values to those observed in the field under similar conditions. Adjustments were made to hydraulic conductivity, river stage, and other parameters prior to simulating pumping, in order to achieve a good comparison between the model and water-level data reported by the U.S. BLM (1977b). In addition to providing some level of certainty, if not calibration, the steady-state simulation was used as the basis for drawdown calculations in subsequent transient simulations. In this case, the only wells present are in an area representing less than 10% of the model area. Cannon (1989) contoured water levels

in the “shallow aquifers” of the Hanging Woman Creek drainage; this area represents about 50% of the upper two layers of the model. Although there was good comparison between those few wells and the steady-state simulation, lack of water-level data for the majority of the model area prevents the calculation of calibration statistics. However, horizontal flow patterns and vertical gradients between layers were judged to be representative of conditions common to coal fields in southeastern Montana.

Ground-water input to the model was based on Darcian flow, calculated from hydraulic conductivities used in the model (Table 2) and the potentiometric surface (Figure 11) presented by Cannon (1989). The flow calculation parameters and results are shown in Table 3. A total northwest flow of 600,000 cubic feet per day was input through cells on the south and southeast edges of the model.

Table 3. Based on Darcy's Law, the calculated steady-state flow through the 4-township width of the model totals 572,770 cubic-feet per day.

Model Layer	Aquifer	K (ft/d)	A (ft^2)	I (ft/ft)	Q (ft^3/d)	Q (gpm)	Q (ac-ft/yr)
1	Overburden	5	7603200	0.01	380160	1970	3190
2	Anderson Coal	3	3801600	0.01	114050	590	960
3	Interburden	0.1	9504000	0.01	9500	50	80
4	Canyon Coal	1.5	2534400	0.01	38020	200	320
5	Interburden	0.1	5702400	0.01	5700	30	50
6	Wall Coal	2	1267200	0.01	25340	130	210
				SUM =	572770	2970	4810

A: area, assumes flow in non-coal units is through 30% of total thickness.
K: hydraulic conductivity, see Table 2.
A: area of aquifer, cross-sectional to direction of flow, see Table 2.
i: potentiometric surface gradient, from Cannon, (1989).
Q: Darcian flow through the specified area of aquifer, (ft^3/d = cubic feet per day; gpm = gallons per minute; ac-ft/yr = acre-feet per year).

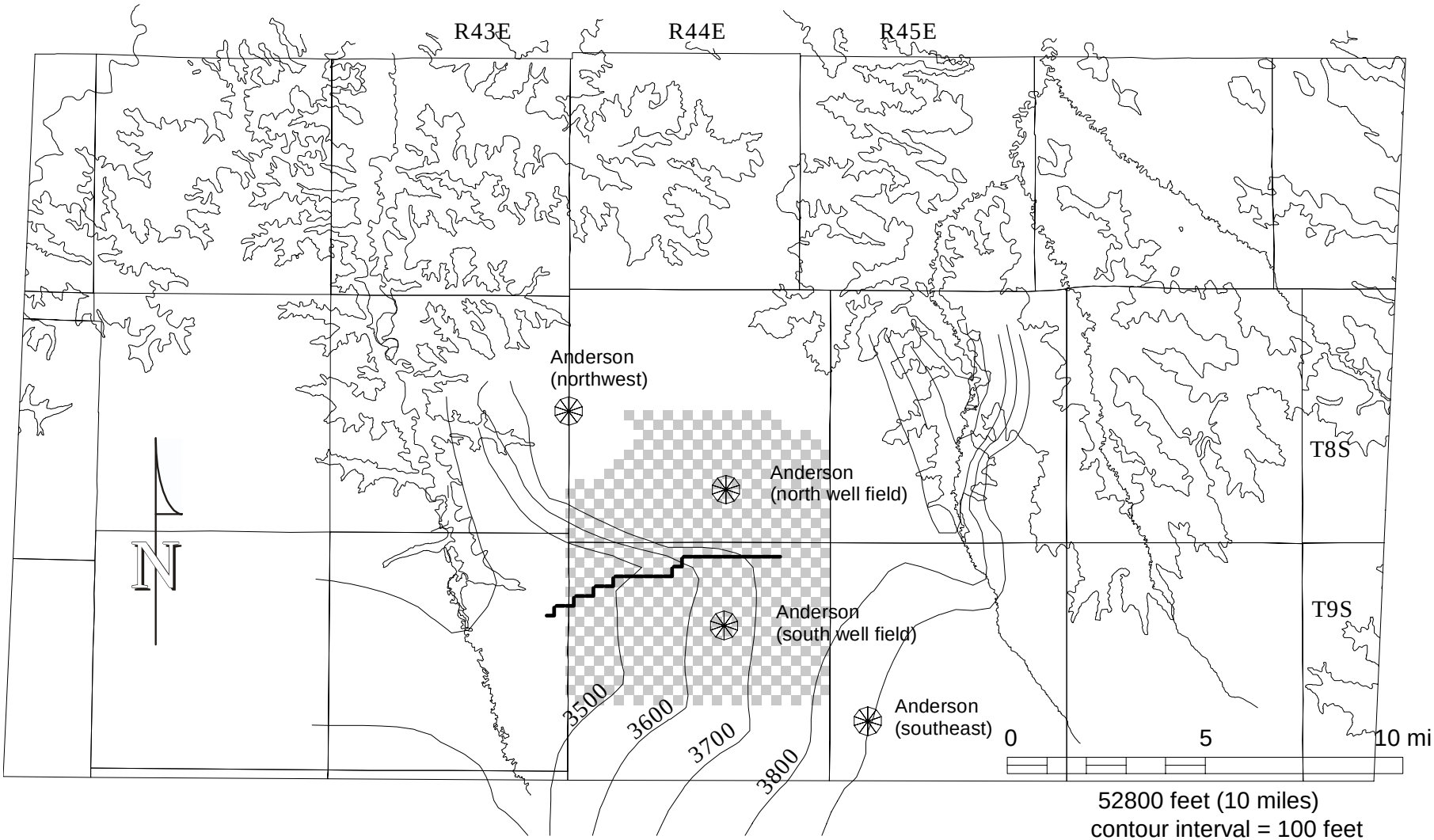


Figure 11. The well field for pumping from the Anderson coalbed allows a 2-mile buffer from the outcrop and lies on either side of the fault (shown as a heavy line). The potentiometric surface represents pre-pumping conditions. Also shown are the locations for hydrographs in figure 18.

Well-field simulation

As noted, the grid spacing of the model was designed to facilitate an alternating, checkerboard 40-acre well spacing, equal to 8 wells per square mile. The Anderson coalbed (layer 2) crops out within the model area, and a minimum 2-mile buffer between the outcrop and the nearest well was maintained (Figure 11); fewer wells in a different pattern were used. The simulated well fields in the Canyon and Wall coalbeds (layers 4 and 6, respectively) included the north half of T9S, R44E and the south half of T8S, R44E (Figure 12). Preliminary modeling of the area indicated a strong influence by the fault on discharge rates; the fault was used to separate the north and south wells fields. Four locations in and around the well fields in each of the coalbeds were selected for observation wells; these are non-pumping wells used to generate hydrographs. A total of 1,082 wells were used to represent pumping from the three coalbeds.

Pumping rates for each well field were based on estimates from a steady-state simulation with all wells pumping. The steady-state condition should reflect maximum drawdown at a given pumping rate used to achieve target drawdown in each coalbed. Pumping rates during the transient simulation were adjusted to achieve the desired range of drawdown over the 20-year life of the well field. Pumping rates ranged from 10 to 20 gpm for the first year and 3 to 20 gpm for the long-term and agree well with published values of 1 to 20 gpm for individual wells in the area (Cannon, 1989). Cumulative water production and pumping rates for the Wall coalbed are shown in Figure 13; overall, pumping rates are higher in the deeper coalbeds than the shallower Anderson coalbed.

Coalbed methane development was simulated in three phases (Table 4 and Figure 13): 10 years of pumping in the south half of the field, then 10 years of pumping in both the south and north halves, and finally, 10 years of pumping only in the north half of the field. Each well field was over-pumped at a rate 1.5 to 2 times the final rate during the first year to induce rapid drawdown. It was necessary to assign different pumping rates to groups of wells in the southern well fields to produce drawdown near the top of the coalbed. A period of no pumping was simulated for 5 years at the beginning and for 10 years at the end to evaluate model stability and aquifer recovery.

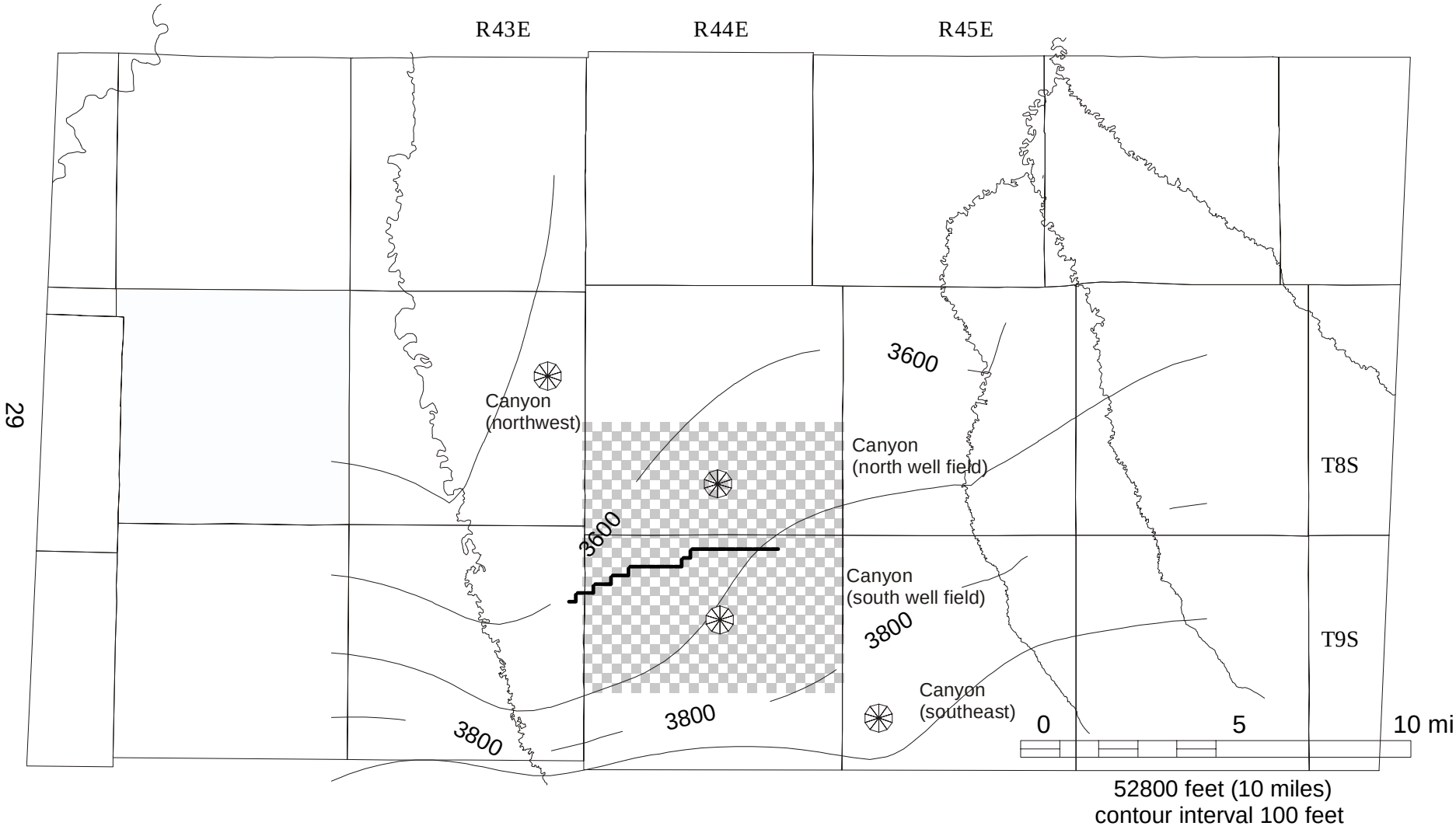


Figure 12. The well field for pumping from the Canyon and Wall coal beds is in the same area as for the Anderson field, but with a larger area since the beds do not crop out in the model area. The potentiometric surface represents estimated pre-pumping conditions for the Canyon coal bed; the fault is indicated by the heavy line. Also shown are the locations for hydrographs in figures 19 and 20.

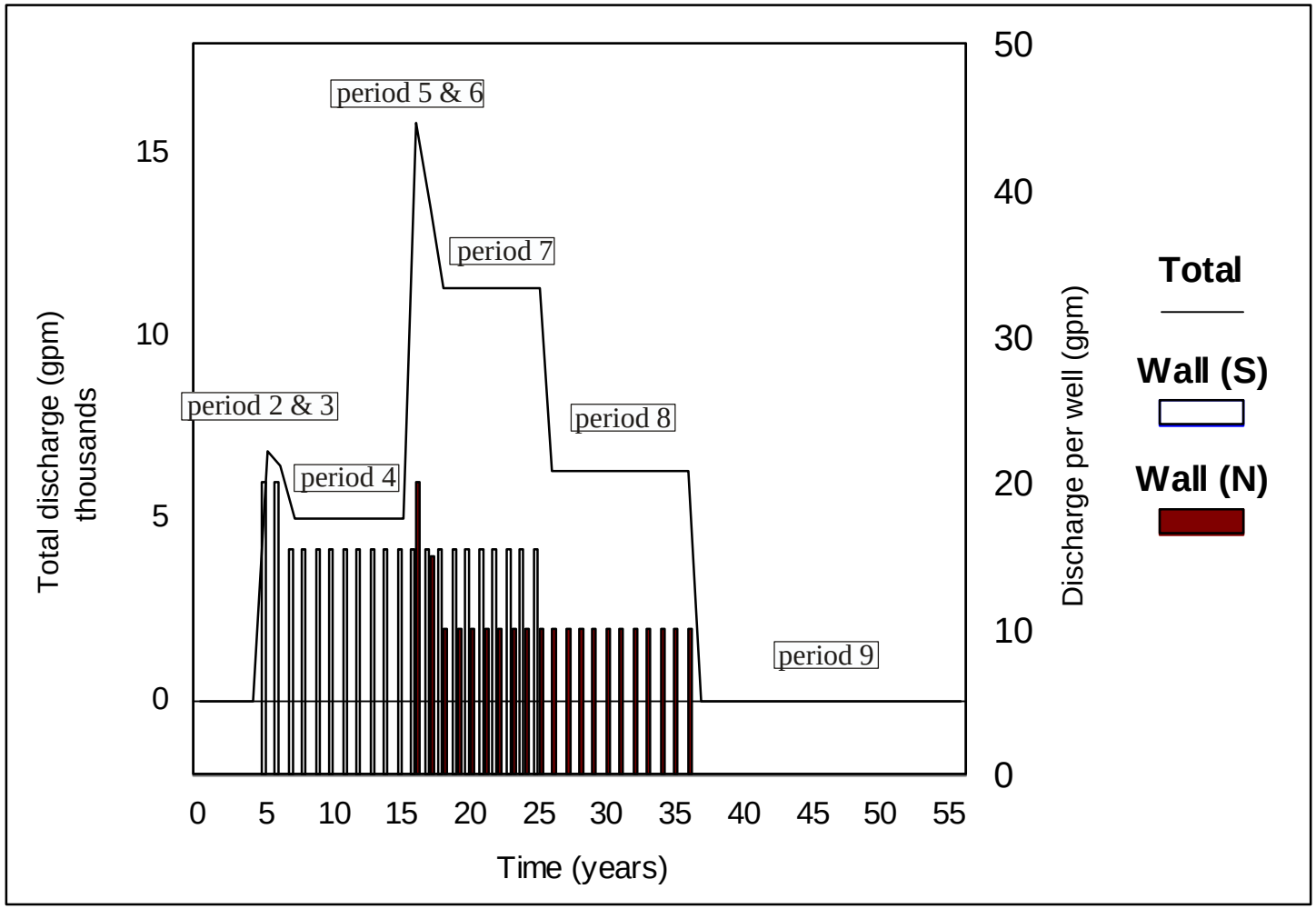


Figure 13. The total production of all wells from the 3 coalbeds (line) is compared to production from the north and south well fields of the Wall coalbed (bars).

Table 4. The model includes nine stress periods.

Stress period	Layer / coalbed	Well field / rate / number	Time (years)
1	all layers	no pumping in any areas	5
2 and 3	2 Anderson	over pumping	1
	4 Canyon	over pumping	
	6 Wall	over pumping	
4	2 Anderson	south: 3-15 gpm; 192 wells north: no pumping	
	4 Canyon	south: 15-20 gpm; 192 wells north: no pumping	
	6 Wall	south: 15-20 gpm; 192 wells north: no pumping	9
5 and 6	2 Anderson	over pumping	1
	4 Canyon	over pumping	
	6 Wall	over pumping	
7	2 Anderson	south: 3-15 gpm; 192 wells north: 10-20 gpm; 114 wells	
	4 Canyon	south:15-20 gpm; 192 wells north: 8 gpm; 196 wells	
	6 Wall	south:15-20 gpm; 192 wells north: 8 gpm; 196 wells	9
8	2 Anderson	south: no pumping north: 10-20 gpm; 114 wells	
	4 Canyon	south: no pumping north: 8 gpm; 196 wells	
	6 Wall	south: no pumping north: 8 gpm; 196 wells	10
9	all layers	no pumping in any areas	10

Model results

Including start-up and long-term pumping rates, water produced during the modeled periods ranges from 3 to 20 gpm per well. For the model 8,100 to 25,500 acre-feet of water per year is projected to be produced from 576 wells and 1,082 wells, respectively. The cumulative water production, after 20 years of pumping from all wells in the model was 400,000 acre-feet.

Figure 14 presents the drawdown in the Anderson coal resulting from 10 years of pumping from the southern half of the well field. This corresponds with the end of step 4 in table 2. The greatest drawdown, about 220 feet, occurred in the area closest to the fault where the coal is deepest; 20 feet of drawdown was produced at a distance of about 2 miles upgradient of the well field and 5 feet of drawdown was produced at distance of about 3 miles. A similar, but less complex pattern, of drawdown developed in the Canyon and Wall coalbeds (Figure 15). The maximum drawdown in the deeper coalbeds was 450 to 550 feet; 30 feet of drawdown was produced at a distance of about 2 miles upgradient of the well field and 5 feet of drawdown was produced at a distance of about 4 miles.

At the end of 25 years (stress period 7, table 2), wells in the south half of each well field had been pumping for 20 years and wells in the north half of each field had been pumping for 10 years. During this period, well interference is greatest and the combined pumping of all wells produced the largest drawdown (Figure 16). Pumping rates in the northern part of the Anderson well field were much less than those of the southern part owing to well interference and shallower coal. The Canyon and Wall coalbeds exhibited drawdown of 450 to nearly 600 feet with the greatest amount in the southern half of the well field (Figure 17). In all cases, the area of influence is close to the well field. Recharge from surface waters is evident in the Anderson coalbed, but much less so in the deeper beds.

Figures 18, 19, and 20 present model-generated hydrographs for observations points in each of the three coalbeds. Maximum drawdowns range from about 240 feet in the Anderson coalbed to about 550 feet in the Canyon and Wall coalbeds. As noted, each well field was over-pumped by 1.5 to 2 times the long-term rate during the first year and is reflected in the steep drawdown curves in the hydrographs of each well field. Model results also indicate drawdown will occur in the overburden and interburden units (Figure 21). As might be expected, the magnitude of the drawdown in the interburden is less than that of the coalbeds, but shows a similar drawdown/recovery hydrograph. Observation wells in the overburden reflect the unconfined nature of the uppermost layer; drawdown in the overburden upgradient (southeast) of the well field was about 6 feet.

In all cases, the upgradient well (southeast) shows influence from pumping; as would be expected, proximity to recharge areas will reduce the impact of pumping. Wells northwest of the well field are downgradient and reflect a lesser influence from pumping.

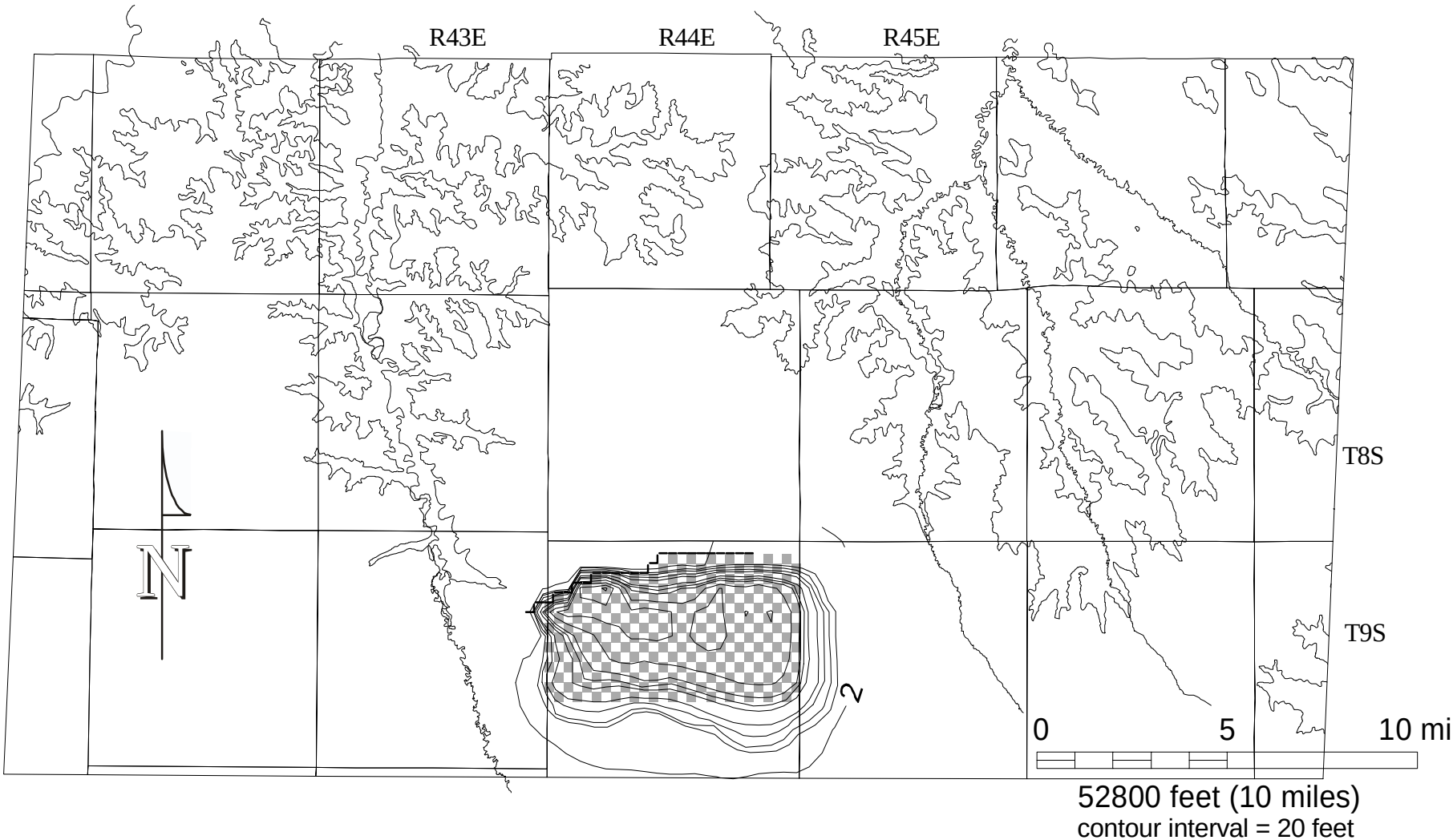


Figure 14. Pumping rates for the well field south of the fault (heavy line) in the Anderson coalbed range from 3 to 15 gpm. A drawdown of about 10 feet is reached about 2 miles upgradient (south) of the well field and approaches the outcrop downgradient after 10 years of pumping.

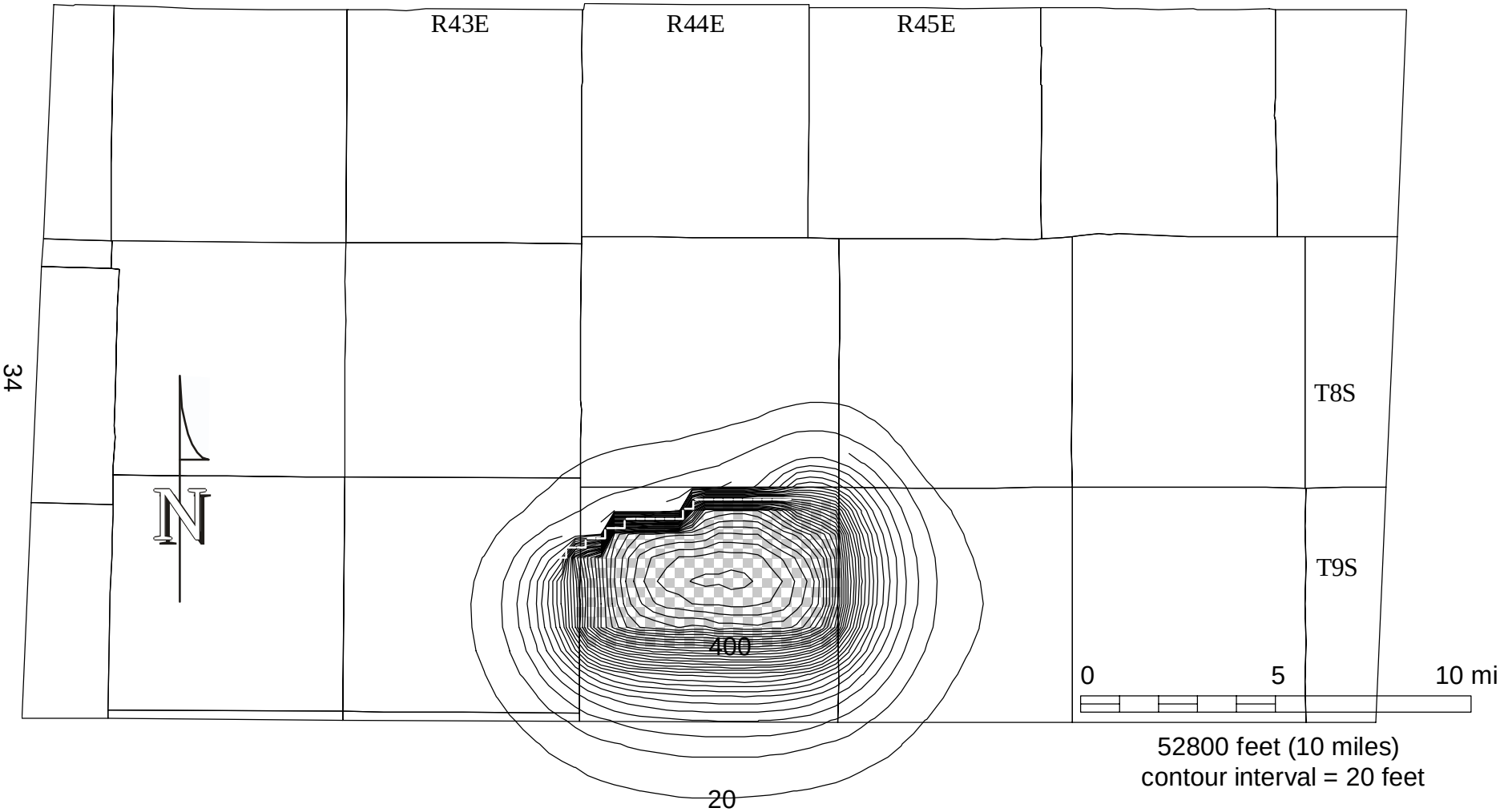


Figure 15. Pumping rates for the well field south of the fault (heavy white line) in the Canyon coalbed averages about 15 gpm. A drawdown of 40 feet is reached about 2 miles upgradient (south) of the well field.

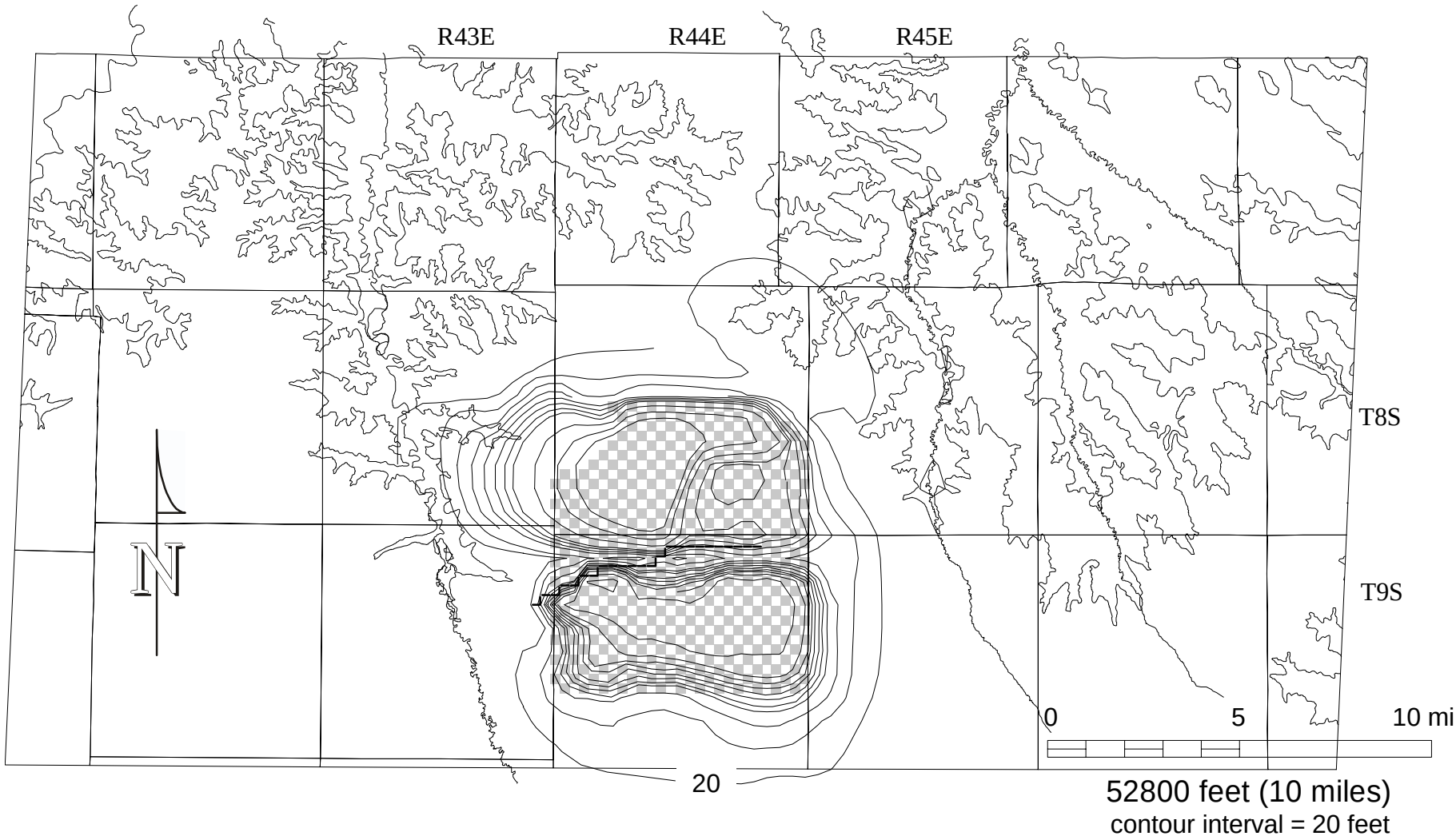


Figure 16. At the end of 20 years, wells in the Anderson coalbed north of the fault (heavy line) have been pumped at an average of 10 gpm for 10 years and wells south of the fault have been pumped for 20 years. A drawdown of about 20 feet has reached about 2 miles south of the well field.

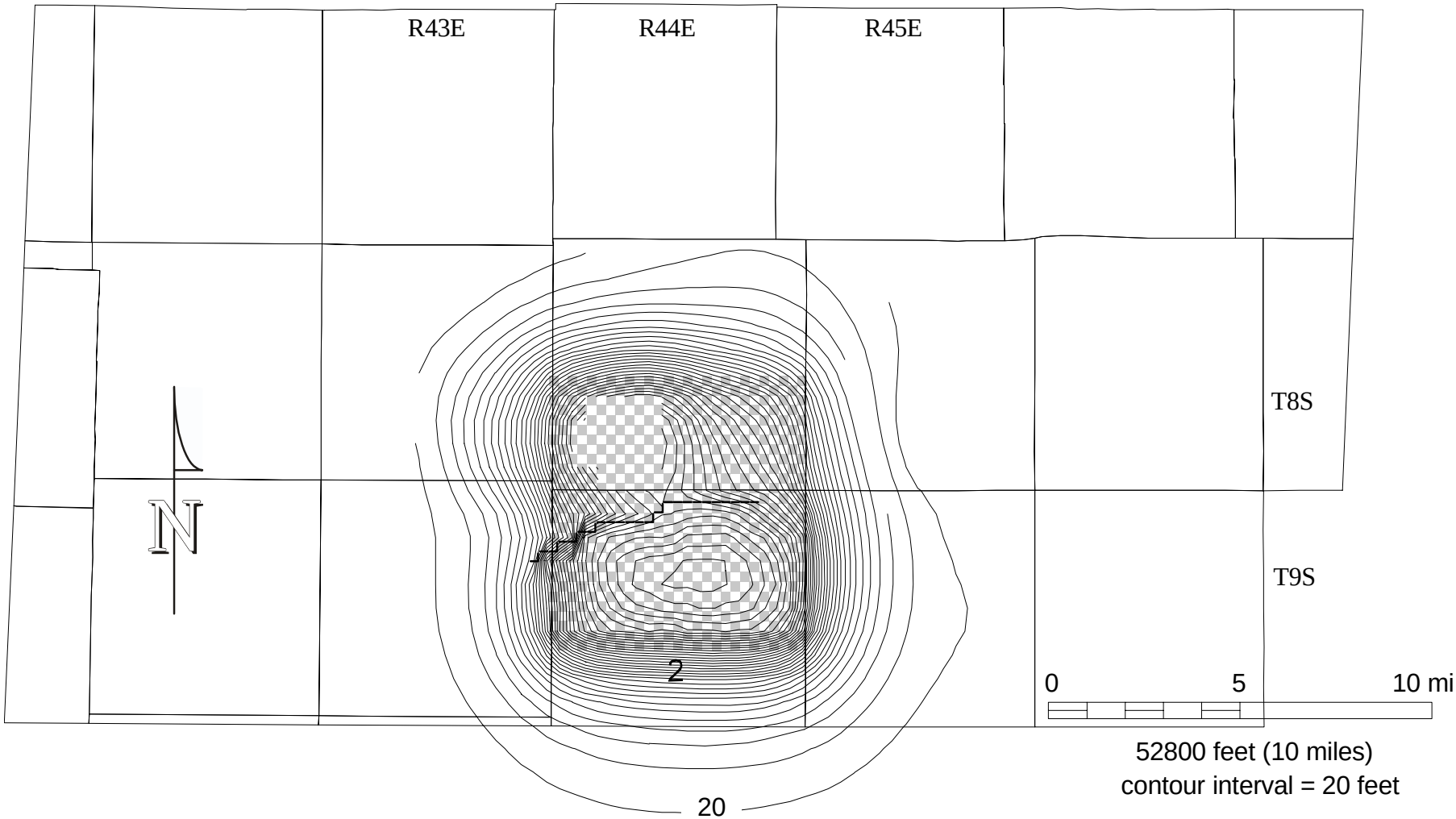


Figure 17. At the end of 20 years, wells in the Canyon and Wall coalbeds north of the fault (heavy line) have been pumped at 8 gpm for 10 years and wells south of the fault have been pumped at an average of 15 gpm for 20 years. A drawdown of 50 feet has reached about 4 miles south of the well field in each of the lower coalbeds.

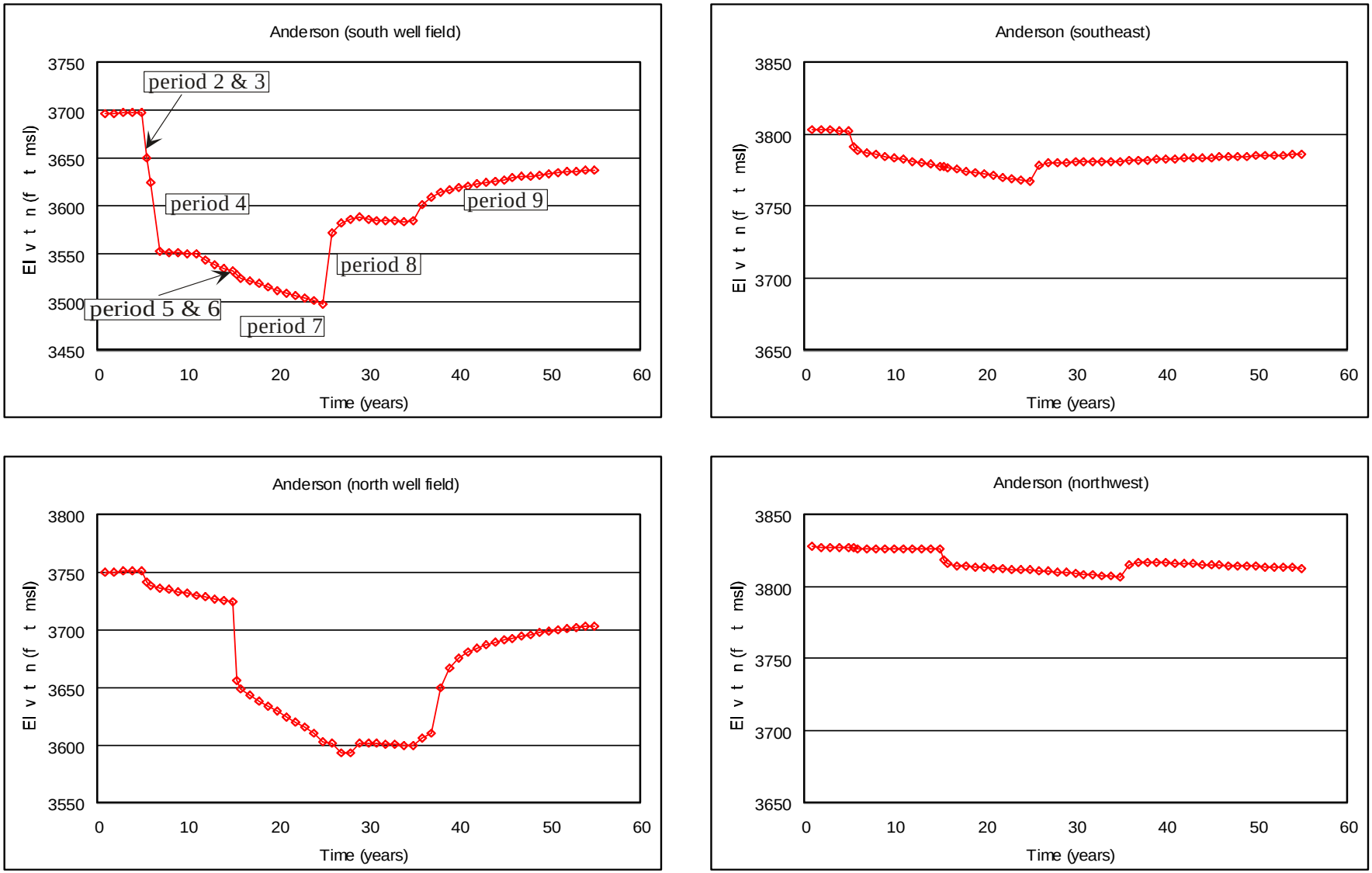


Figure 18. The Anderson coalbed is represented by Layer 2 of the model. The location of each observation point is indicated in figure 11. The well-field hydrographs show the effect of over-pumping to induce rapid drawdown. The stress periods indicated on the first hydrograph are described in table 2.

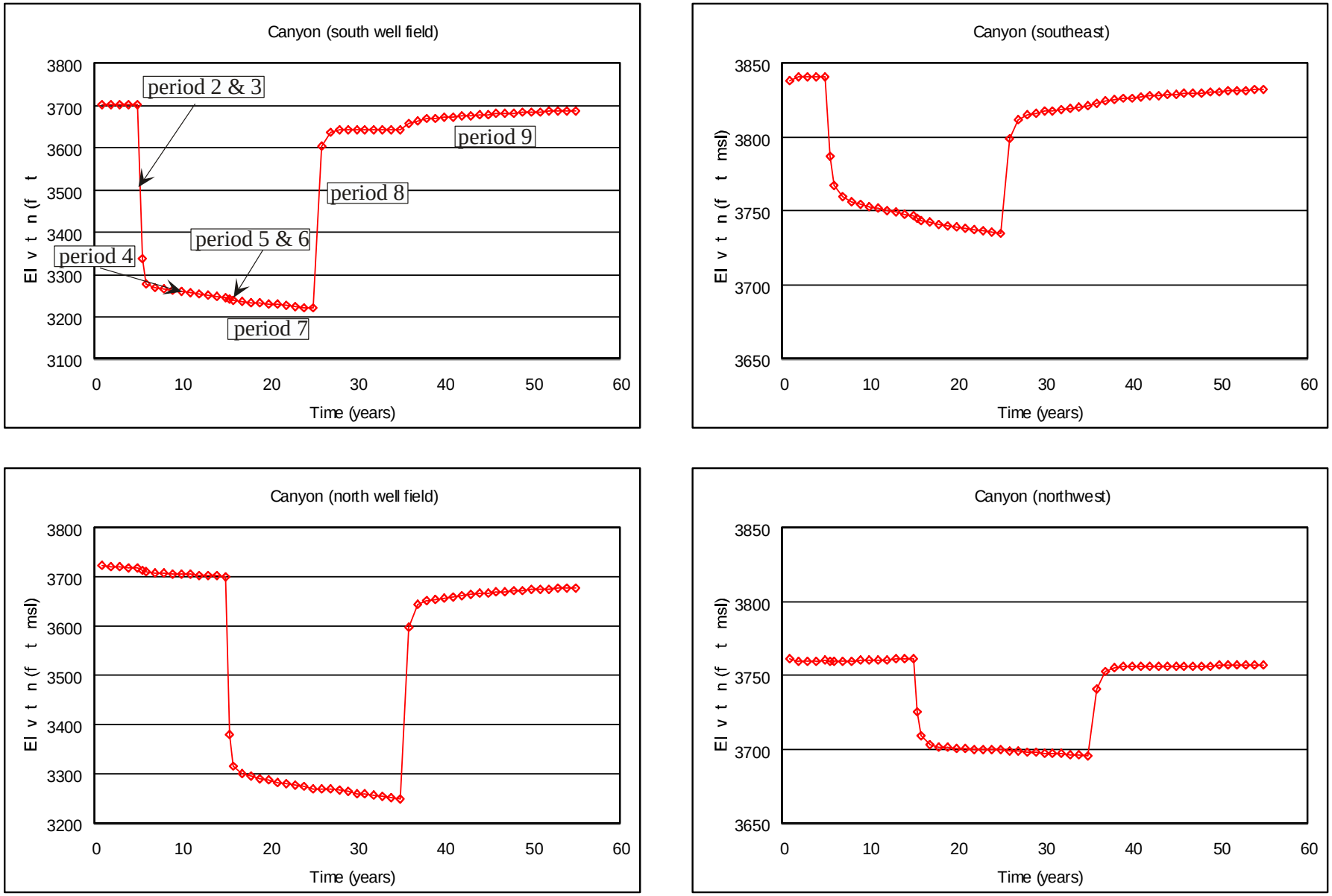


Figure 19. The Canyon coalbed is represented by Layer 4 of the model. The location of each observation point is indicated in figure 12. The stress periods indicated on the well field hydrograph are described in table 2.

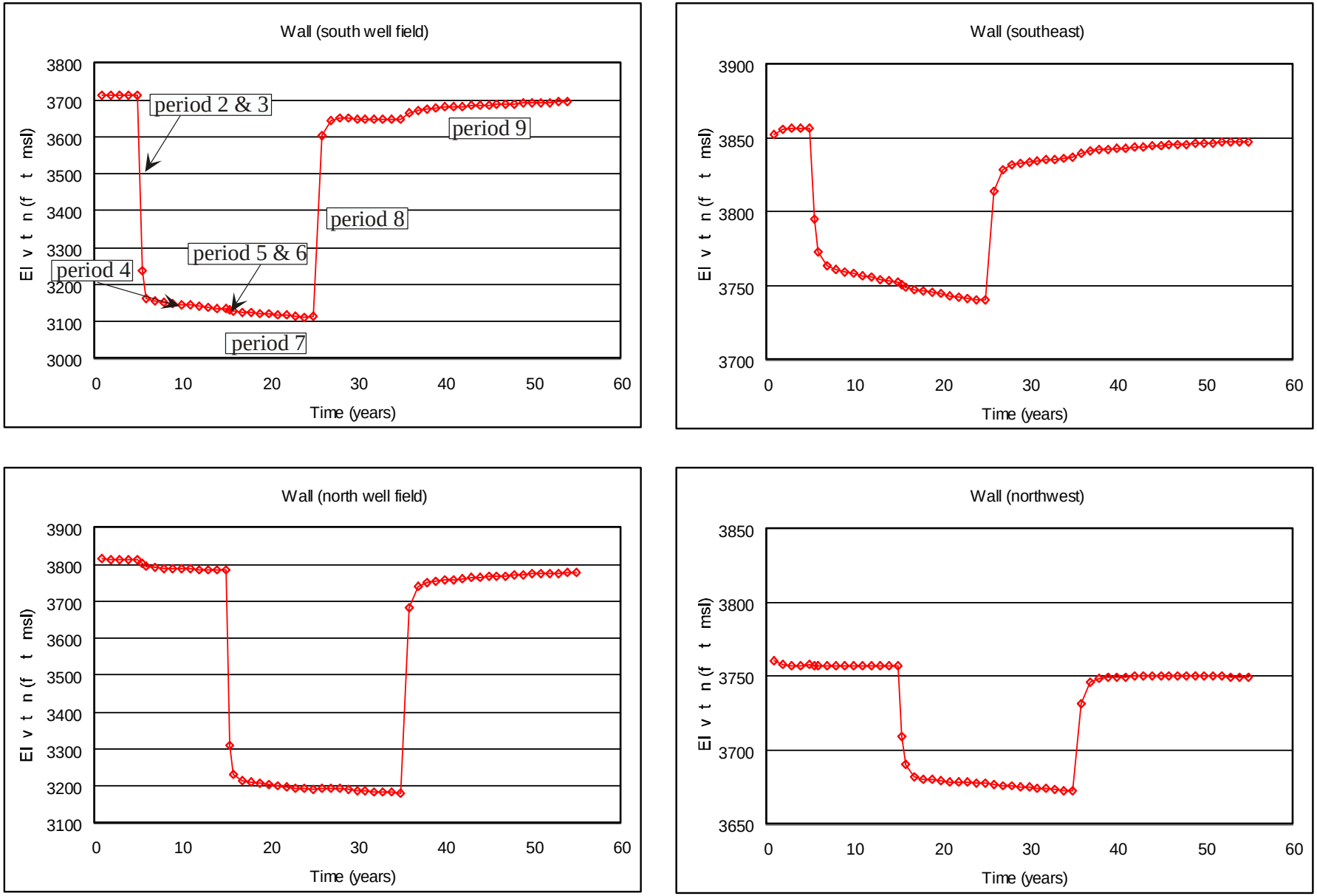
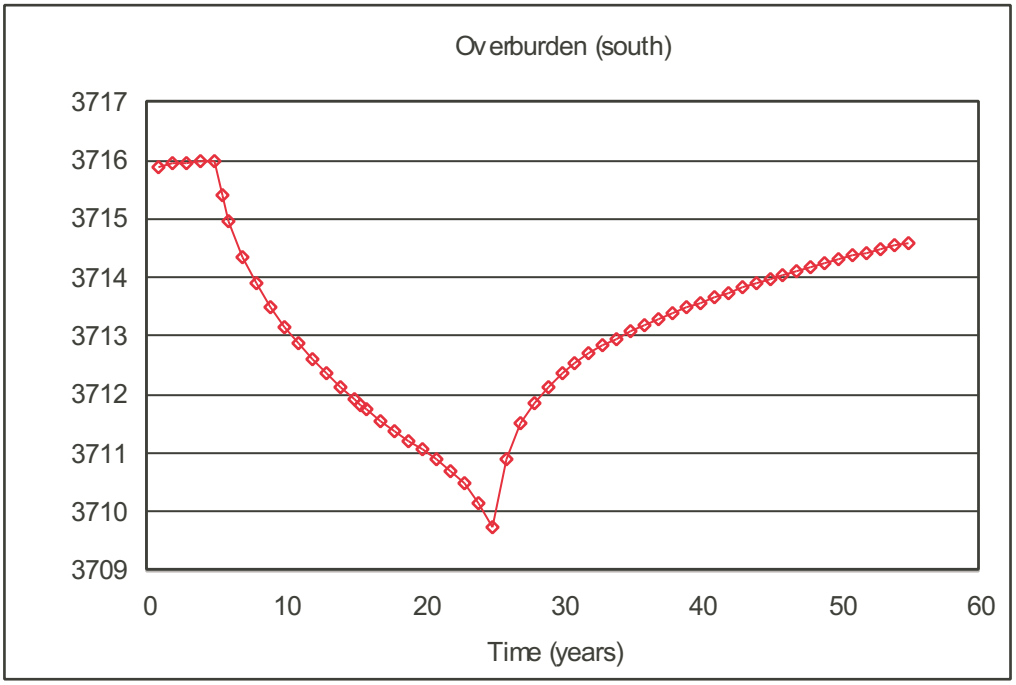


Figure 20. The Wall coalbed is represented by Layer 6 of the model. The location of each observation point is the same as those for the Canyon in figure 12. The stress periods indicated on the well field hydrograph are described in table 2.



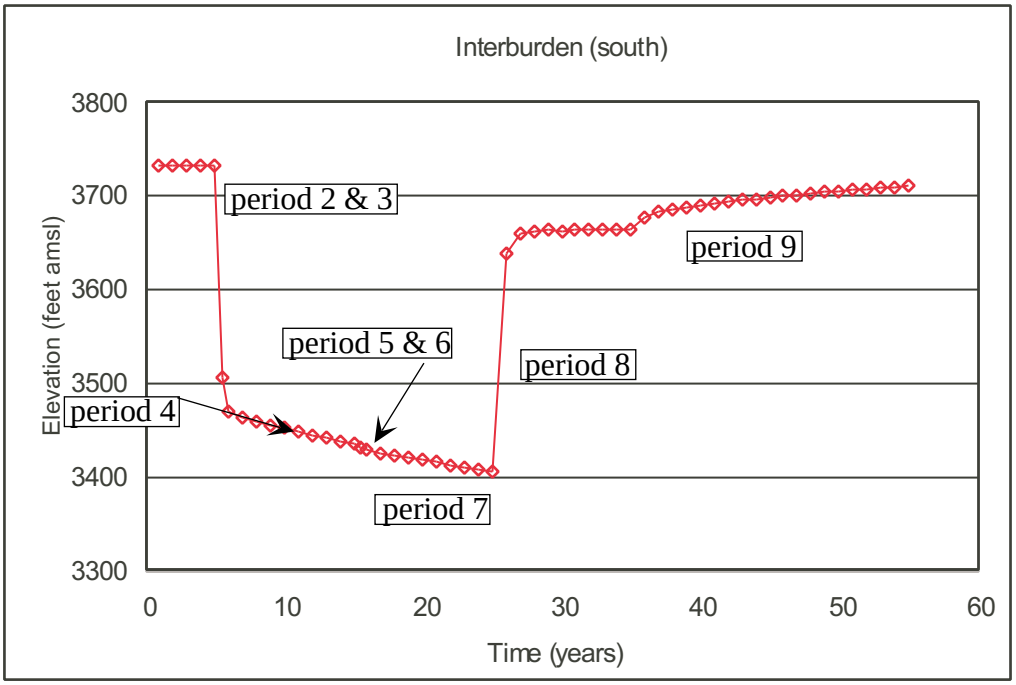


Figure 21. The “overburden” is represented by Layer 1 of the model. The hydrograph for the interburden is from Layer 3 of the model in the area of the south well field.

After pumping ceases, water levels recover in the model. After 10 to 12 years water levels in the Anderson Coal within the well fields are typically within about 70 percent of pre-development water levels. At a distance of about 2 miles outside the production fields, available head in the Anderson recovers to about 90 percent of per-development levels within 2 to 3 years. Drawdown during production decreases with distance from the CBM field, therefore, recovery demands are less and recovery occurs quicker at greater distances from the field. In both the Canyon and Wall coals, water levels recover to within about 90 percent of pre-development levels within about 5 years after pumping ends. Recovery in overburden and interburden units is similar to the adjacent pumped coal seams.

Water-level recovery occurs from redistribution of water in storage in the aquifer and from recharge. Complete water-level recovery will not occur until recharge water reaches in impacted area. Regional scale development upgradient of the modeled well field would reduce the water and hydrostatic pressure available for recharge and the recovery times would increase.

Sensitivities to violations of assumptions

Coal aquifers are not homogeneous and isotropic, as assumed here. Real conditions will cause the shape of the cones of depression around CBM fields to have irregular shapes, extending farther in the directions of highest hydraulic conductivity. Errors and lack of data for aquifer parameters will cause erroneous model results. Higher values of transmissivity will allow greater discharge rates and larger drawdown, and higher storativity will create smaller cones of depression and larger discharge rates.

The most important parameter that may be violated by real world conditions is vertical leakage. To date, no vertical hydraulic conductivity data are available for the Powder River Basin in Montana. Vertical leakage from overlying (or in some cases underlying) aquifers will decrease the drawdown effects, accelerate recovery and allow larger discharge rates. As noted, the vertical hydraulic conductivity is assumed to be 10% of the horizontal hydraulic conductivity in the coalbeds and 1% of the horizontal hydraulic conductivity in the overburden and interburden for this model. Even a very small vertical hydraulic conductivity value can have a very strong effect. However, based on conditions near Decker, vertical leakage from units near ground surface is thought not to be a major factor. There, drawdowns in coal beds pass un-interrupted beneath perennial streams (Squirrel Creek and Tongue River) and the associated alluvial valley floors. Water-table levels in the alluvium and a shallow sandstone unit have not responded to coal-mine induced drawdown.

Model discussion

The limitations of a computer-generated model are reflected in the assumptions made in the construction of the model. In this case, the coalbeds and interburden were assumed to have uniform thickness, aquifer parameters were assumed to be uniform, and regional recharge/discharge relationships were assumed to be constant. The well locations and pumping schedule used here, with large blocks of wells coming on-line at the same time, may not reflect the best design with respect to pipeline placement and discharge control. Development would be expected to begin in the south and move north, however, this may not be the case. The modeled scenario does not take into account mineral ownership or other factors that affect development plans. The model evaluated an isolated CBM field, whereas development in Wyoming indicates that new fields typically are developed adjacent to other fields or mines to take advantage of existing drawdown. All of these factors affect well placement and timing, and therefore will alter the anticipated impacts to ground-water systems. Limitations of the model code prevent an evaluation of such phenomena as fluid density changes due to de-gassing, aquifer compression due to long-term pumping, and bio-film growth and decay due to chemistry changes, which may also affect pumping rates and drawdown. Similarly, the code used in this simulation considers only porous media and ignores fracture-dominated flow that may exist in areas of faulting.

Faults near Decker have been shown to be no-flow boundaries (Van Voast and Reiten, 1988). In this model faults are simulated by offsetting the layers and cells near the fault are assigned a horizontal-flow barrier.

Within the limitations described, the model does provide a means to demonstrate, though not predict, some of the hydrologic conditions that may be encountered in coalbed methane development. The regional ground-water gradient, which tends to reflect structural gradients, exerts a measurable control on the shape of the zone of influence. The presence of faulting within a well field, which is common, will strongly determine pumping rates.

Development of coalbed methane fields requires a non-traditional approach to ground-water development. Methane production requires the reduction of the hydrostatic pressure or head within the formation to provide optimum degassing and delivery to the borehole. Pumping rates are based on the resulting drawdown required for production, and wells are placed within the zones of influence of adjacent wells to induce additional drawdown. The ultimate pumping rate of a given well within a well field is determined by several factors including :

- Well spacing: Most designs, as is the model presented here, are based on uniform spacing of production wells. Geologic structural features such as faults and folds or surface features such as streams and roads may prevent a uniform spacing of wells. A non-uniform distribution of wells will affect the shape and

extent of the overall drawdown pattern and the pumping rate of any given well will depend on its spatial relationship with the other wells and the feature in question.

- Pumping rate distribution: If the objective of a well field is to induce a uniform pattern of drawdown, well discharge in the center of a well field will be less than discharge from wells on the outer edge of the field. Similarly, wells in the upgradient area of the field would require more discharge than those on the down-gradient side of the well field. These considerations are in addition to the variations in aquifer properties.

- Timing: the model presented here assumes one-half the entire well field in all three coalbeds is in place before any pumping begins. Variations on the timing would certainly affect the rate of drawdown and expansion of the zone of influence. The long-term pumping water levels, however, would not be changed.

Each of these factors can be included in a site-specific model, but requires a site-specific design and a significant effort of trial and error. Since there is likely to be more than one solution to a set of conditions, other factors outside the model, such as cost or legal considerations, will further constrain the final design.

In spite of the limitations inherent with models of this type, valuable conceptual information can be obtained as to conditions to be expected with future development. Summarized in this report are a list of those conditions, which can likely be projected to areas of the Powder River Basin.

Summary

Coalbed methane production represents a new and potentially important industry in Montana. However, in the Powder River structural basin, coal seams are important aquifers that are widely used by the agricultural community and provide water for wildlife. Understanding and anticipating the potential impacts from coalbed methane development is critical to informed, beneficial-decision making by resource managers. Data collected during the past 30 years provide a foundation to estimate impacts to coal aquifers. The data provide actual measurements of existing impacts and provide input used to calculate likely future impacts.

The purpose of this report is to present an example of potential ground-water impacts from the development of coalbed methane (CBM) within the Powder River Basin in southeastern Montana. The coal seams in the Tongue River Member of the Fort Union Formation in southeastern Montana, unlike gas reservoirs in other areas or settings, are also the principal local aquifers. Ground-water issues include: 1) decrease in available water resources due to reduction in hydrostatic head in coal aquifers; 2) quantities of CBM-produced water and disposal of that water; and 3) ground-water recovery and restoration of the hydrologic balance.

Based on reviews of impacts from coal-strip mining, CBM impacts in Montana and Wyoming, and ground-water modeling in this report, CBM production in Montana can be expected to have significant impacts on local hydrogeology in the Powder River Basin of Montana. The following list summarizes the anticipated ground-water conditions.

- Future CBM production can be expected to cause water-levels to decline to near the tops of the coal seams throughout the producing fields.

- Drawdown of more than 10 ft within the coal aquifers can be expected to reach 1 to 2 miles outside the producing fields during the early years of production and distances of 5-10 miles, or more, during long-term production.

- Overburden and interburden aquifers may also experience drawdown, but to a lesser degree than the producing coal seams.

- Flows from springs and the water available at wells supplying water for livestock, domestic and wildlife uses will be diminished or eliminated within the areas of drawdown. The decrease in yield will be proportional to the decrease in hydrostatic pressure in the aquifer at the well or spring.

- Discharge rates from individual CBM wells will vary depending upon time since pumping began, position in the field, size of the CBM field and local aquifer conditions.

- For isolated CBM fields of roughly 1,100 wells, discharge rates can be expected

to be between 3 to 20 gpm per well, and cumulative rates may be as high as 25,000 acre-feet per year at start-up and 8,000 acre-feet per year for long-term production, depending on the number of wells brought on line per year.

- Discharge water quality will be dominated by ions of sodium and bicarbonate, with only small concentrations of other constituents.

- Recovery of water levels in aquifers will begin when CBM production ends. Extent and timing of recovery will depend on distance from the CBM well field, extent of development, proximity to recharge, and aquifer characteristics. Complete recovery will require much more time within the CBM well field than outside the field.

- Based on the modeled scenario presented in this report of an isolated, 1-township sized CBM well field, available head will likely approach 90 percent of pre-development levels after about 5 years outside the production area. Within the CBM field, recovery will take longer, and may approach 70 percent within 10 to 15 years.

- Size of the CBM field, and distance from recharge areas will strongly affect recovery rates. If regional depletion of the ground-water levels occurs, the time required for recovery of water levels within the CBM fields will be significantly longer than indicated by the model presented here.

Steady-state modeling has a limited applicability to CBM impact assessments. Transient, 3-dimensional modeling provides an indication that drawdown will be significant, discharge rates will decrease with time, and recovery will take many years. The model presented in this report is generic, and does not necessarily represent actual impacts that will likely occur due to CBM development in the Hanging Woman Creek area. By using aquifer characteristics that are typical for the Powder River Basin, the results of the model provide general values of drawdown, pumping rate, and recovery for CBM development in the structural basin for the size of the well field considered. The model was used to evaluate an isolated CBM field. Actual development in Montana will most likely be similar to other CBM developments, with adjacent fields covering large areas. For this reason, the model probably underestimates drawdown outside the field and overestimates water production from CBM wells, and underestimates the time required for recovery to occur.

Generally, both storativity and hydraulic conductivity (both horizontal and vertical) are crucial to understanding the magnitude of potential impacts. Storativity has a stronger effect on the calculations than does horizontal hydraulic conductivity. The effect of vertical hydraulic conductivity is similar to that of storativity, and the lack of data for vertical hydraulic conductivity is a serious issue with a multi-layer model. Size of development is less important since the cone of depression outside a CBM field expands as field size increases, but at a rate of expansion that is less than the rate of expansion of the CBM field.

Discharge rates should not be discussed without an associated time frame. Both hydrogeologic theory and ground-water modeling show that discharge rates will decrease with time, and this should be included in any discussion of disposal. Also, any wells near the center of a field will have lower discharge rates than those near the edge of the field which are intercepting regional ground-water flow. Therefore the average discharge per well will decrease with time and will decrease as the total number of adjacent wells increases. For these reasons, discharge rates are probably best discussed in terms of cumulative volume discharged in specific years of development, rather than the average volume produced per well over the life of the project.

This assessment is thought applicable to other areas of the Powder River Basin depending on aquifer properties, aquifer recharge processes, and well-field design. Coalbeds in areas of Montana other than the Powder River Basin may well have very different characteristics and this report may not be directly applicable to those areas. Also, impacts expected in the Tertiary Fort Union Formation may be of only limited relevance to Cretaceous coals in Montana. Site-specific data will need to be compared to the data used in this report to determine the transferability of these results.

One of the results of this report that is transferable to all CBM areas is the need for monitoring data. Modeling and comparison of data from other areas can only provide a preliminary understanding of the potential impacts. Actual monitoring is the only method to determine and document impacts and lack of impacts, thereby improving predictive capabilities and allowing implementation and adjustment of sound water-management plans. Monitoring wells should be installed and measured regularly in producing coal seams outside development fields, and in overlying and underlying aquifers both within and outside the CBM fields. Only through monitoring will the debate on impacts be translated to actual information.

Data and interpretations presented in this report provide a framework to discuss hydrogeologic impacts of CBM development in the Powder River Basin of Montana. A full understanding of these impacts will require:

- geologic data related to structure, faults, and lithology
- hydrologic data related to ground-water, streams, and springs
- a preliminary model to identify data gaps and to assist in the design of monitoring programs
- a monitoring plan based on the model, the well-field development plan, and public needs
- implementation of the monitoring plan coincident with CBM development
- revision of the model based on monitoring data and evaluation of impacts from continued development
- continued evaluation of the impact and recovery from CBM development
- public dissemination of interpretations of the data.

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