Methane production from coal beds accounts for almost 8% of the total methane production in the United States (Van Voast, 2003) and is a relatively new, but important industry in the Powder River Basin in southeast Montana and northeast Wyoming (Figure 1). Coalbed methane is formed in the coal by either biogenic or thermogenic processes. If the coalbed is buried deeply, generally greater than 30m, and there is sufficient hydrostatic pressure, the methane will remain adsorbed on cleat surfaces and in micro-pores in coal (Rice, 1993; Rightmire et al, 1984). The gas is held in place by weak attractive forces between the coal and the gas and by hydrostatic pressure from ground water in the coal. To produce the gas, water is pumped from wells completed in the coal, the hydrostatic pressure is reduced, and the gas is desorbed. 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 and the gas flows up the well casing to be extracted by 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 3.2 km$^2$ and consists of 10 to 15 wells completed in each coal seam, or about one production well per 0.32 km$^2$ 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. In southeastern Montana, coal seams hold two valuable energy resources (mineable coal and coalbed methane), but also ground water that is vital to a large agricultural economy. Proper, equitable management of these resources necessitates development of hydrologic impact predictions. The effects of long-term, sustained well-yields over areas of coalbeds that may exceed townships in size are undocumented in Montana.

Computer-generated ground-water flow modeling was used to demonstrate potential drawdown, discharge rates, and recovery of a 100 km$^2$ coalbed methane production field. The MODFLOW program (McDonald and Harbaugh, 1988) and a pre/post processor, Ground Water Vistas (Rumbaugh and Rumbaugh, 1998) were used to develop a 3-dimensional ground-water flow model of the Hanging Woman Creek area in southeast Montana. Hydrologic characteristics for this area are similar to other areas of the Powder River Basin. There are at least three roughly parallel coalbeds capable of producing methane dipping at a nearly uniform gradient of 0.004 toward the southwest. The coalbeds are separated by as much as 50 meters of interburden sandstones and claystones. Several normal faults in the study area have displacements greater than the thickness of the coalbeds and thus, affect well placement, discharge rate, and the drawdown pattern. The model grid was set up for 0.16 km$^2$ spacing in the central area to allow 0.32 km$^2$ well spacing commonly used in coalbed methane development. The grid spacing was 402 meters 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 2,200 meters and a maximum row width of 10,000 meters. 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. The final version of the model consisted of 31,200 active cells for a 30-year simulation. To simulate progressive development, production, and decommissioning, coalbed methane development was simulated in three phases: 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. Including start-up and long-term pumping rates, water produced during the modeled periods ranges from 11 to 76 liters per minute per well. The model simulated a total production of 10,000,000 to 30,000,000 cubic meters of water per year from 576 wells and 1,082 wells, respectively. The cumulative water production, after 20 years of pumping from all wells in the model was 4.9 billion cubic meters.

In the 20-year life of the production fields, pumping produced about 6 meters of drawdown at a distance of 3.2 kilometers (Figure 2). The maximum drawdown in the deeper coalbeds was 135 to 165 meters; 9 meters of drawdown was produced at a distance of about 3.2 kilometers and 1.5 meters of drawdown was produced at a distance of about 6.4 meters. Twenty-five years after pumping is stopped, water levels in the shallowest coalbed recovered about 70%. Figure 3 presents model-generated hydrographs for wells in the shallowest of the three coalbeds.

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 production field, whereas development in Wyoming indicates that new fields typically are developed adjacent to other fields or mines to take advantage of

![Figure 2](image.png)

Figure 2. At the end of 20 years, wells in the Anderson coalbed north of the fault (heavy line) have been pumped at an average of 40 L/min for 10 years and wells south of the fault have been pumped for 20 years. A drawdown of about 6 meters has reached about 2 kilometers south of the well field.

![Figure 3](image.png)

Figure 3. The Anderson coalbed is represented by Layer 2 of the model. The well-field hydrographs show the effect of over-pumping to induce rapid drawdown. The stress periods are indicated on the first hydrograph.

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 in coalbeds 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.

References


