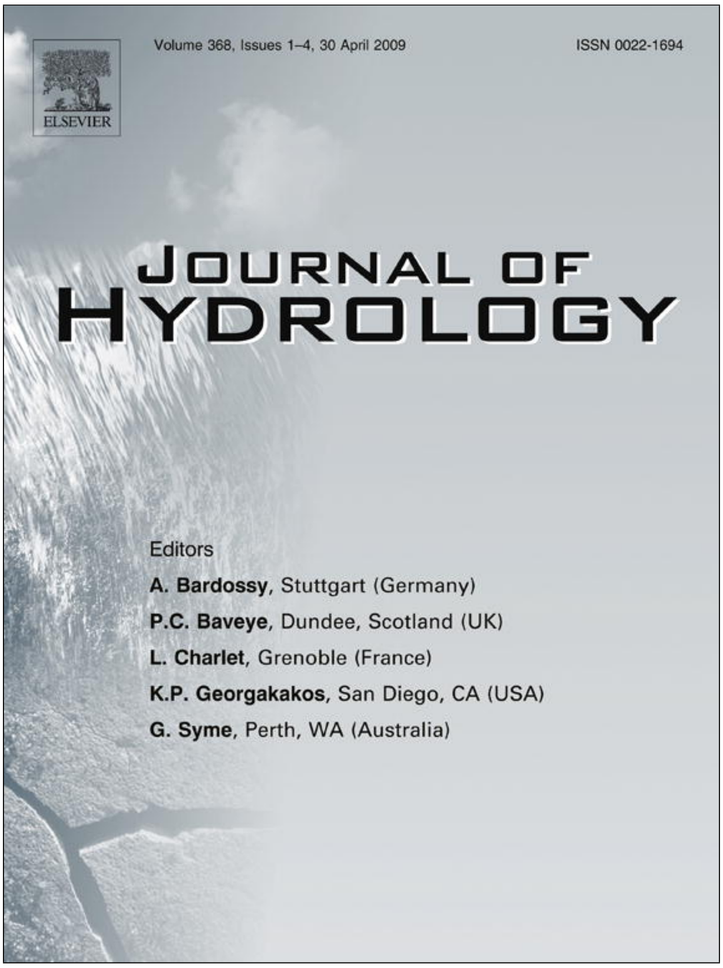
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Groundwater management and coal bed methane development in the Powder River Basin of Montana

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SUMMARY

Coal bed methane (CBM) development will eventually pump more than 124,000 ha-m of groundwater, or more than 40% of the recharge, from the coal seam and sandstone aquifers of the Montana portion of the Powder River Basin (PRB). This will relieve the hydrostatic pressure, by causing a drawdown in the potentiometric surface and drawing groundwater from storage and natural discharges, to release the methane gas. A numerical groundwater flow model simulated drawdown that will exceed 90 m in the middle of the CBM fields with 6-m drawdown extending up to 29 km from the fields. Simulation results indicate that river flux will decrease up to 40% and drawdown will encompass hundreds of wells and springs. Recovery requires up to 45 years for significant decreases in river flux to recover and is not complete for 200 years. CBM development impacts can be mitigated in two ways. First, reinjecting produced water into depleted coal seams would replenish the lost storage so that recovery would draw less groundwater from long distances. Second, rapid infiltration basins near potentially-affected rivers could decrease the short-term river flow depletion. Modeled artificial recharge replaced up to 4000 ha-m of deficit in the depleted coal seams and is a feasible option for mitigating some effects of CBM development. Reinjection would be more effective if the development period were lengthened.

Introduction

Coal seams underlie much of northeastern Wyoming and eastern Montana (Flores and Bader, 1999). Methane gas formed in these coal seams and was trapped by groundwater at high pressure. Coal bed methane (CBM) development extracts methane gas by pumping groundwater to lower the hydrostatic pressure and release the methane.

CBM development began in the Powder River Basin (PRB) of Wyoming in the early 1990s. Widespread CBM development in the Montana PRB began in 1999 at the CX Ranch well field (Fidelity, 2004) (Fig. 1). At full development, the Montana PRB could have almost 25,000 CBM production wells (BLM, 2007), which would potentially produce more than 1,100,000 ha-m (ALL, 2001) of groundwater.

Much of the CBM water is discharged to surface water. Most hydrologic-related research has focused on the water quality of this discharge, primarily the high salinity and sodium adsorption ratio (McBeth et al., 2003; Wang et al., 2007). However, CBM development removes groundwater from valuable aquifers and causes a potentially substantial drawdown. CBM wells are spaced as close as 32 ha/well over thousands of hectares and pump from 8 to 80 l/min (Wang et al., 2007) causing drawdown that could extend many kilometers (AHA and Greystone, 2002). This drawdown could increase pumping lift and decrease stream- and spring-flow (BLM, 2007; ALL, 2001).

This paper considers the observed and modeled extent that drawdown has and could extend from the CBM fields and the potential impacts on springs and streamflow that could occur due to full development of CBM in the Montana PRB. Springs and streams currently support the water rights of this agriculturally-based basin. Also considered are mitigation benefits of recharging up to 50% of the produced water into depleted coal seams or sandstone layers between the coal seams.

Methods of analysis

Powder River Basin of Montana

The PRB consists of sedimentary rock with little deformation (Downey, 1984, 1986). It lies at the juxtaposition of the Rocky Mountains and Great Plains and has been affected by mountain uplift. Basement rock under the sedimentary rock of the PRB is as deep as 3000 m below sea level (Downey, 1984, 1986). The Fort Union, the primary surface and coal-bearing formation of the region, was deposited in fluvial environments including braided, meandering, and anastamosed streams in the center of the basin, and alluvial plains along the basin margins (Flores et al., 1999). The Fort Union formation consists of interbedded sandstone,

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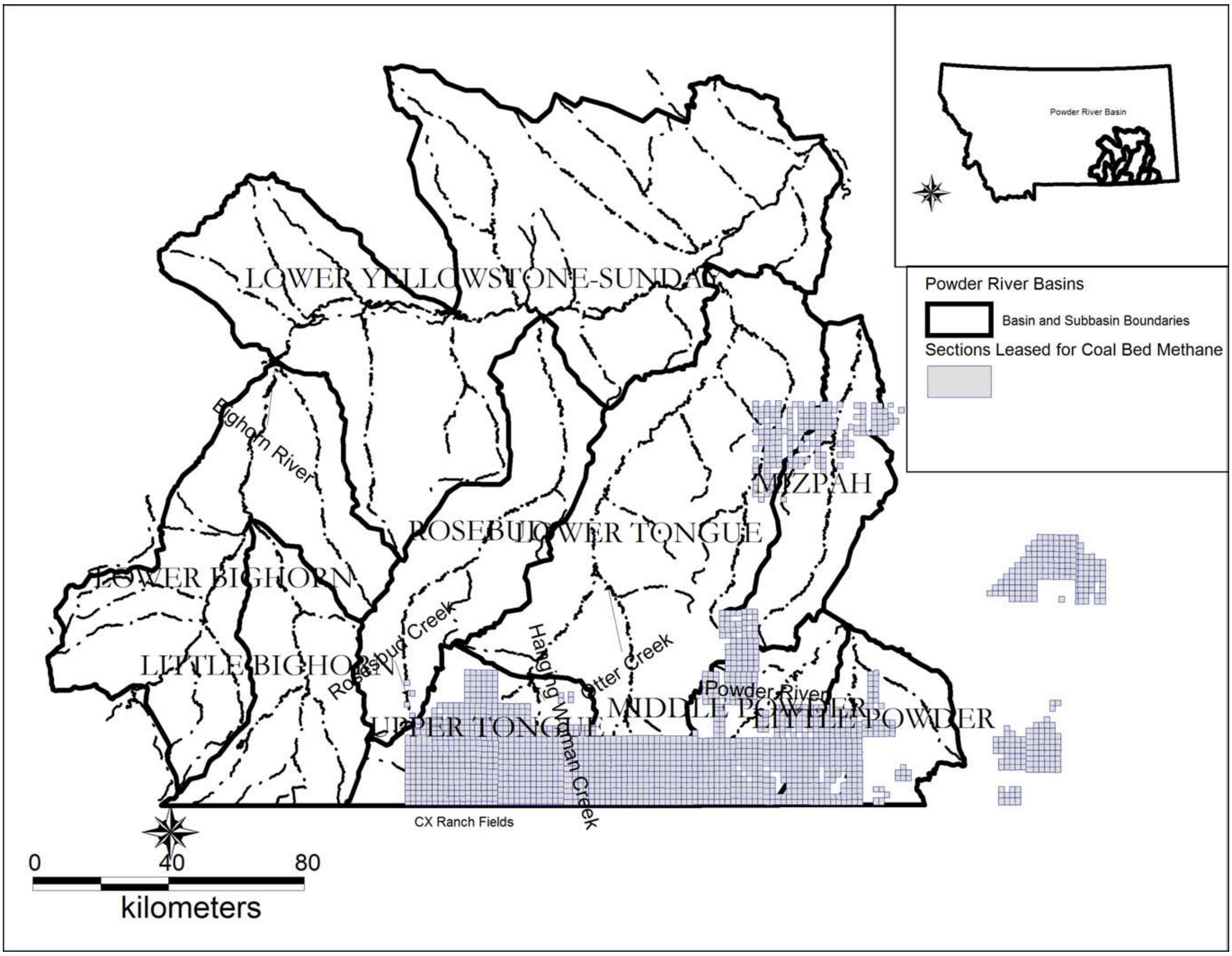

Fig. 1. Powder River Basin of southeast Montana showing the sections that have been leased. Sections are one-mile square (1.6 km square).

mudstone, occasional shale, and coal (Roberts et al., 1999). Faults cross much of the southwest portion of the Montana PRB (Roberts et al., 1999), and some may be flow barriers (Fidelity, 2004), especially where they offset the stratigraphic layers.

All coal seams, including, from shallowest to deepest, the Smith, Anderson/Dietz, Canyon/Monarch, Cook, Lower Cook, and Wall coal seams (Roberts et al., 1999) are CBM development targets (Wheaton and Metesh, 2002). The Anderson and Dietz 2 and the Dietz 3 seams merge in various locations, such as the CX Ranch and Decker coal fields (Roberts et al., 1999), and become very thick. The Dietz 2 and 3 become thin and vanish east and northeast of the CX Ranch while the Anderson extends across the Hanging Woman Creek basin. The Knobloch is the lowest principle coal bed in the Tongue River Member of the Fort Union formation. Approximately 300 m of interburden and coal seams lies between the Knobloch and the Anderson (Donatu and Wheaton, 2004a,b). Coal seam thicknesses vary substantially (Roberts et al., 1999), but analysis of well logs available from the Groundwater Information Center (GWIC) of the Montana Bureau of Mines and Geology (http://mbmggwic.mtech.edu) show coal seam thicknesses vary up to about 30 m (Fig. 2).

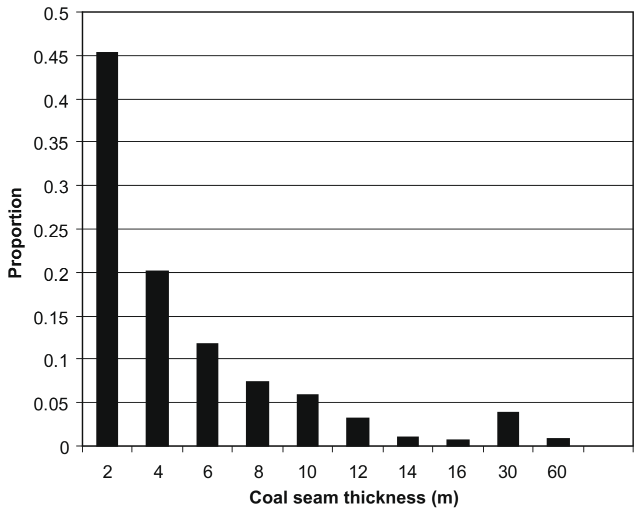

Fig. 2. Histogram of coal seam thickness.

Conceptual model of flow in the Powder River Basin

Groundwater flow occurs through the layered coal seam and sandstone aquifers from the points of recharge in the headwaters of the basin in Wyoming and on the uplands between the rivers to the discharge points from the various rivers, streams, and

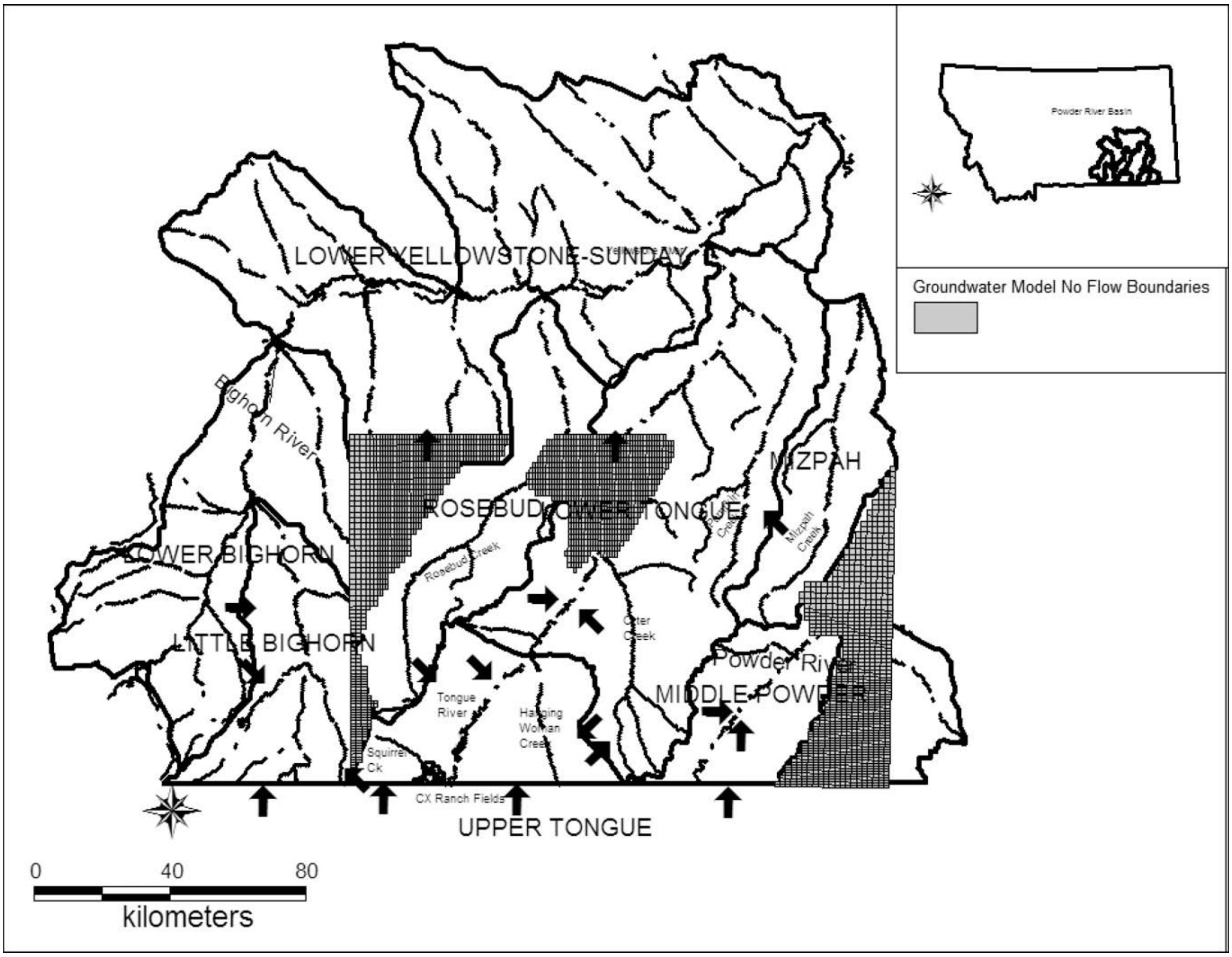

Fig. 3. Powder River Basin and sub-basins, rivers and streams, conceptual groundwater flow model, and groundwater model domain.

springs (Fig. 3). Coal seams either outcrop along canyon walls forming springs or intersect and discharge into alluvium under the rivers. Based on an observed gradient (0.021) and estimated conductivity (0.3 m/d) (AHA and Greystone, 2002), the average pre-development flow from the PRB headwaters in Wyoming across the border to Montana is approximately 63 m^3/d/km for the 9 m thick Anderson coal seam.

The hydrologic properties of coal seams as compared with nearby sandstone aquifers make them important regional aquifers supporting many wells. Coal has a high secondary permeability and relatively high bulk conductivity but a low matrix permeability (Weeks, 2005). Coal has a high specific storage ($2.0 \times 10^{-5}\ m^{-1}$ to $1.5 \times 10^{-4}\ m^{-1}$) compared to standard values for fissured rock (Anderson and Woessner, 1992), but relatively low porosity (0.02), and releases groundwater very slowly (Weeks, 2005).

Hydraulic conductivity in the Anderson coal, the shallowest coal seam, varies from 0.12 m/d (Stoner, 1981) to 5.5 m/d (Weeks, 2005). Stone and Snoeberger (1977) found the conductivity in the Felix coal approximated 0.2 m/d. Weeks (2005) estimated conductivity in the Flowers-Goodale coal at 2.2 m/d. These researchers also found significant horizontal anisotropy. Morin (2005) found that bedding configuration likely controlled the anisotropy rather than cleat directions as postulated by Stone and Snoeberger (1977).

Natural aquifer recharge

Recharge in the PRB occurs in three ways. The first is diffuse net recharge, the difference between infiltration and evapotranspiration, across the basin (Singh, 1989). The second is infiltration/recharge of runoff flowing in streams and rivers (Flint et al., 2004). The third is a special case of the first: recharge through clinker outcrops (Bartos and Ogle, 2002).

Recharge may be estimated by assuming that the baseflow represents groundwater discharge at close to steady state, a valid assumption in a regional-scale system (Cherkauer, 2004) dominated by spring runoff and baseflow. A complicating factor is that different geologic layers intercept portions of the recharge in the PRB causing it to discharge at different locations, where the layers outcrop. Baseflow in large rivers therefore represents discharge originating as recharge in many different parts of the PRB. Smaller basin discharge represents local recharge more accurately. Average October flow on small basins most accurately represents baseflow because the surface runoff, interflow, and irrigation are minimal and because the streams will not have begun to be affected by ice and snow.

Baseflow indicates the highest recharge occurs in the drainages that head in the Big Horn Mountains, Lodgegrass Creek, and the Little Bighorn River, all on the west side of the basin (Table 1). The Tongue River at State Line station has much higher rates than those

Table 1
October flows, drainage area, and computed recharge for US Geological Survey Montana Powder River Basin Gaging Stations (USGS flow data from http://waterdata.usgs.gov/mt/nwis/sw/).

Gage number	Name	Area (km^2)	Avg flow (m^3/s)	Recharge (cm/y)
06325500	Little Powder River near Broadus	5113	0.19	0.12
06324710	Powder River at Broadus	22657	7.02	0.97
06324500	Powder River at Moorhead	20943	6.37	0.95
06307500	Tongue River at Stateline	3763	7.11	5.9
06306100	Squirrel Creek	87	0.02	0.72
06295113	Rosebud Creek	319	0.08	0.79
06294000	L Bighorn near Hardin	3351	4.36	4.1
06289000	L Bighorn at Stateline	471	2.45	16
06291000	Owl Ck near Lodge Grass	422	0.11	0.82
06291500	Lodge Grass Creek	209	0.60	9.05

based on discharge from local basins, which reflects conditions in the Big Horn Mountains. Baseflow at the Owl Creek, Rosebud Creek, Squirrel Creek, and Powder River stations better represent recharge in the Montana PRB.

Elevation varies by less than 700 meters and precipitation varies by only about 10 cm across the PRB. Recharge equals about 0.8 cm/y across the Montana portion of the PRB, based on the observed baseflow (Table 1). Large-scale precipitation-based variability is likely to be low, but geology controls the specific location of recharge. More will occur in clinker and through ephemeral stream bottoms.

Groundwater discharge

The PRB drains northward toward the Yellowstone River, and the lower reaches of major rivers gain flow due to groundwater discharge. Several rivers such as the Powder River, Tongue River, Hanging Woman Creek, and Rosebud Creek flow north and have eroded into and through the Fort Union formation (Fig. 3). Baseflow in these rivers depends on groundwater discharge. Four gages along the Tongue River with long records still in use during 2004 adequately represent the discharge to the Tongue River within Montana. November flow data best represents this discharge in the Tongue River because it is less variable than in October, the month analyzed for recharge, presumably because the variable return flow from riparian irrigation has slowed. Through the stream reaches of the lower Tongue River, baseflow discharge increases only slightly indicating the groundwater discharge to this reach is low (Fig. 4). For example, the Birney-to-Miles City reach drains 51% of the entire PRB, or 7120 km^2, and the median baseflow increases by only 0.66 m^3/s. This reflects the low elevation in the north portion of the PRB (Fig. 4) and the fact that recharge to the deeper coal seams which outcrop in these reaches occurs far to the south, in Wyoming, where only a small amount of recharge reaches the deeper coal seams.

Coal seams outcrop along the terraces and cliff faces (Donatu and Wheaton, 2004a,b). The confined aquifer transitions to phreatic and many springs emanate from various formations. Within the study area, Donato and Wheaton (2004a,b) inventoried 688 springs and found that 450 of them were flowing. The maximum observed flow rate was 0.94 l/s. Some springs are local, which means they receive local recharge and have variable flow rates. Other springs are regional as demonstrated by their steady flow.

Groundwater movement and response to stress

Coal mine dewatering and CBM development causes the most substantial groundwater development in the PRB, as noted by monitoring wells maintained by the Montana Bureau of Mines and Geology (Fig. 5). Coal mine dewatering caused long-term drawdown of as much as 15 m over 20 years in well WR-54, followed by about 40 m in 6 years of CBM development (Fig. 6). Rapid drawdown to as much as 70 m has occurred to well WR-27 within one-half km of a CBM field (Fig. 6). Drawdown is substantial but occurs more slowly in wells more than one-half km from a CBM field (Fig. 6, WR-53). Alluvial wells next to perennial streams, such as WR-54A, show changes in response to seasonal runoff and evapotranspiration. The hydrograph of WR-18A, screened in overburden next to an ephemeral tributary to Squirrel Creek, displays erratic changes that can be explained as recharge from flow events on the tributary. Most alluvial wells have responded little within the first years of CBM development.

The rate that coal seam monitoring well levels respond to CBM development depends on their distance from the CBM fields and the depth of the coal seam. Close-in wells experience rapid water level drops consistent with the drawdown cone quickly developed by the production wells. It happens quickly because maximum CBM production depends on rapidly depressurizing the seams. Coal seam wells farther from the CBM development drawdown slower as a function of the hydrologic properties between the monitoring well and CBM field. Leakage from the over- or underlying aquifers may also affect the propagation of drawdown, as documented and modeled in Wyoming (AHA and Greystone, 2002).

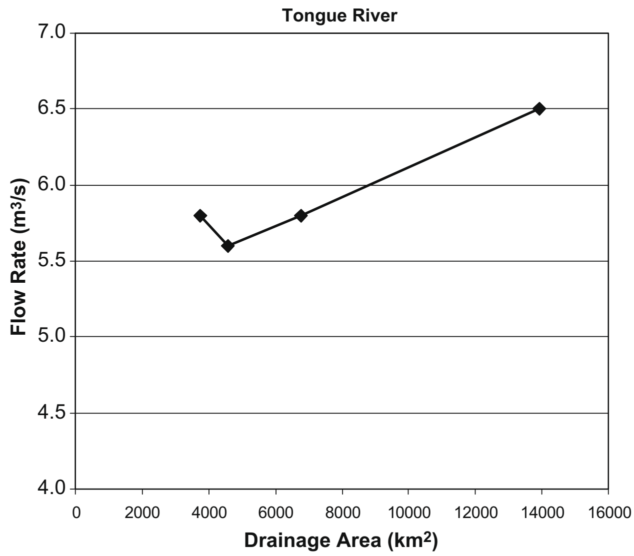

Fig. 4. Relation of median flow rate to drainage area for US Geological Survey gaging stations on the Tongue River. From smallest area to largest area, the stations are Tongue River at State Line near Decker (6306300), at Tongue River Dam near Decker (6307500), at Birney Day School near Birney (6307616), and Tongue River at Miles City (6308500), all in Montana.

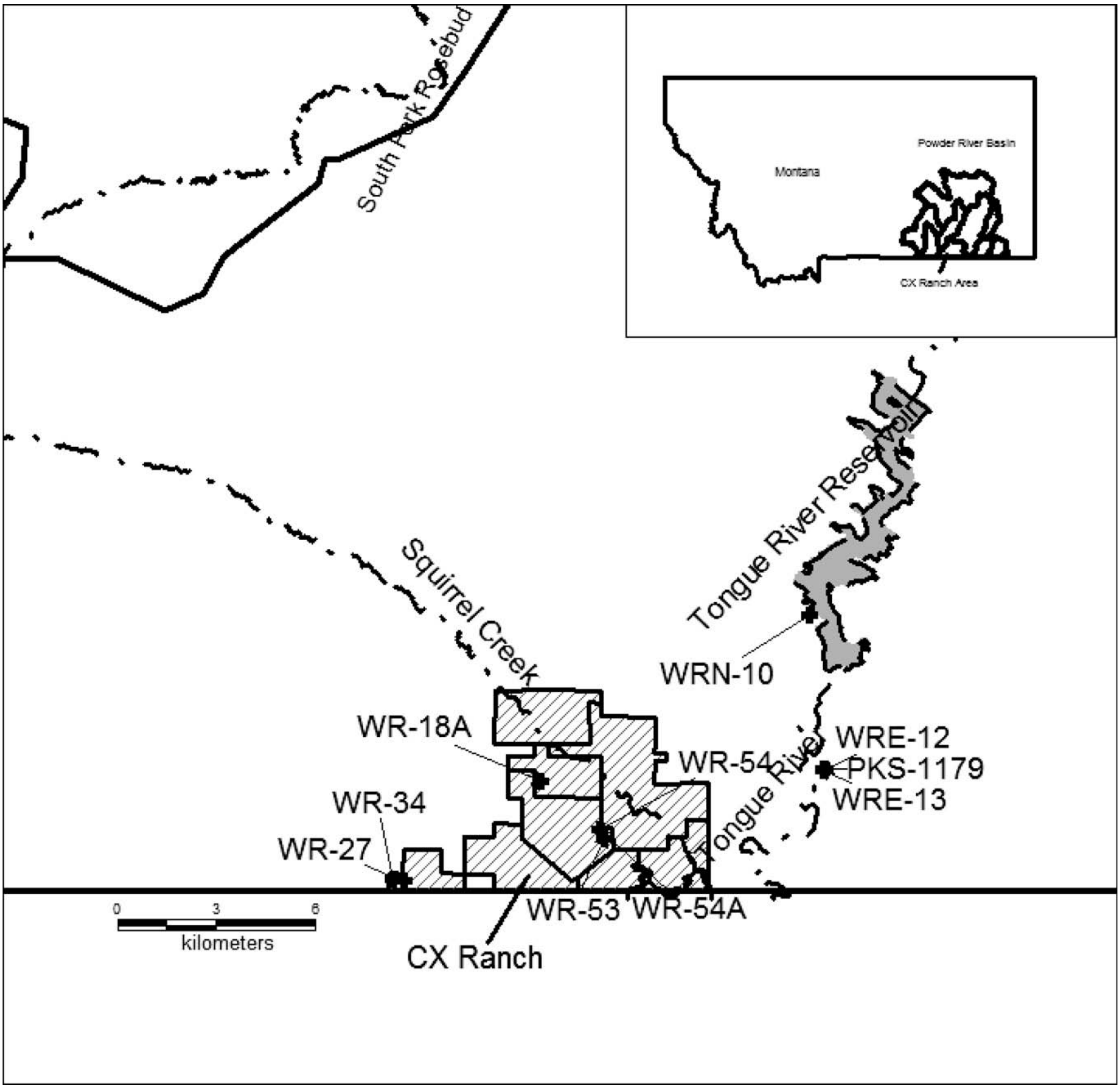

Fig. 5. Location of selected monitoring wells in the CX Ranch area and near the Tongue River. See Figs. 6 and 7 for hydrographs of these wells.

Changes in stage at the Tongue River Reservoir affect the water level in nearby coal seam aquifers (Wheaton and Donatu, 2004; van Voast and Hedges, 1975; van Voast and Reiten, 1988) as confirmed at monitoring wells near the Tongue River and Tongue River Reservoir. For example, water levels at wells WRE-12, WRE-13, and PKS-1179, screened in Anderson/Dietz coal, vary with the reservoir, coal mining, and CBM. Early variations of up to 3 m paralleled seasonal reservoir-level changes (Fig. 7). Beginning in 1980, mine dewatering began to dampen the seasonal changes and lower the water levels. The rate of decline increased due to nearby CBM development in early 2003. Water levels in the deeper Dietz seam well (PKS-1179) dropped about 21 m after CBM development began resulting in a total drop of about 43 m. Water levels at well WRN-10, screened in clinker and Dietz coal very close to the Tongue River Reservoir, vary seasonally up to 8 m (Fig. 7). Induced surface water leakage probably has dampened the declines due to dewatering and CBM development.

Vertical gradients

Observed water levels show a downward gradient among coal seams but not between the overburden and the Anderson coal seam (Fig. 8a and b). Water levels slope downward to the north (Fig. 8a) as does the ground surface, but up to the east under the higher ridges. Wheaton and Donatu (2004) noted a downward gradient at some observation wells in the Hanging Woman Creek area and an upward gradient north of Birney. The downward gradient represents ongoing recharge through the aquifer layers and the upward gradient occurs in the vicinity of groundwater discharge to the Tongue River, discussed in 'Groundwater discharge'.

Groundwater flow model

A groundwater model numerically (Harbaugh et al., 2000) simulating the conceptual flow model of the basin was developed to

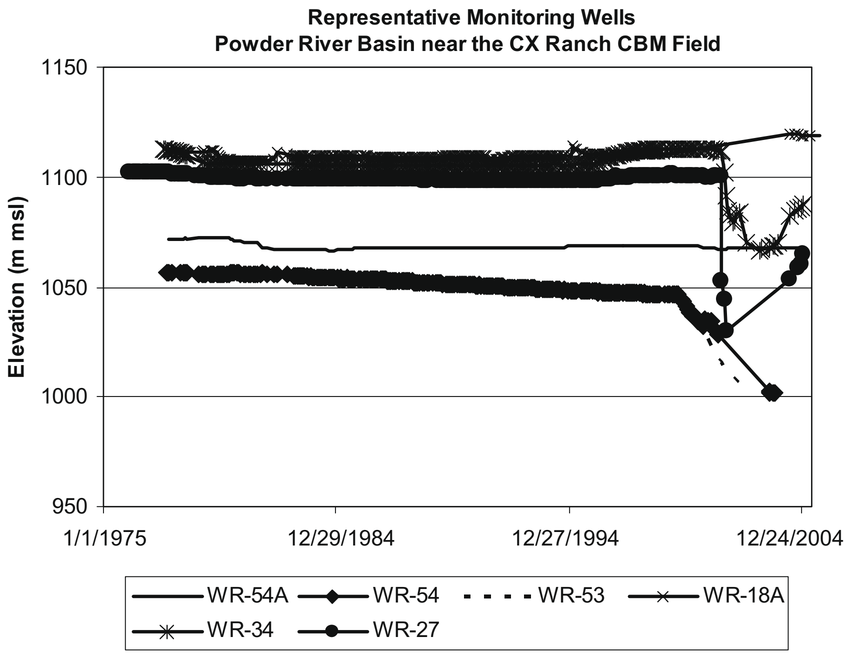

Fig. 6. Hydrographs of selected monitoring wells in and near sections leased for CBM development. WR-54a is 64 m deep screened in Anderson overburden; WR-54 is 117 m deep screened in Dietz; WR-53 is 117 m deep screened in Dietz coal; WR-18a is 34 m deep screened in alluvium; WR-34 is 159 m deep screened in Dietz coal; WR-27 is 111 m deep screened in Dietz coal. See Fig. 5 for their location.

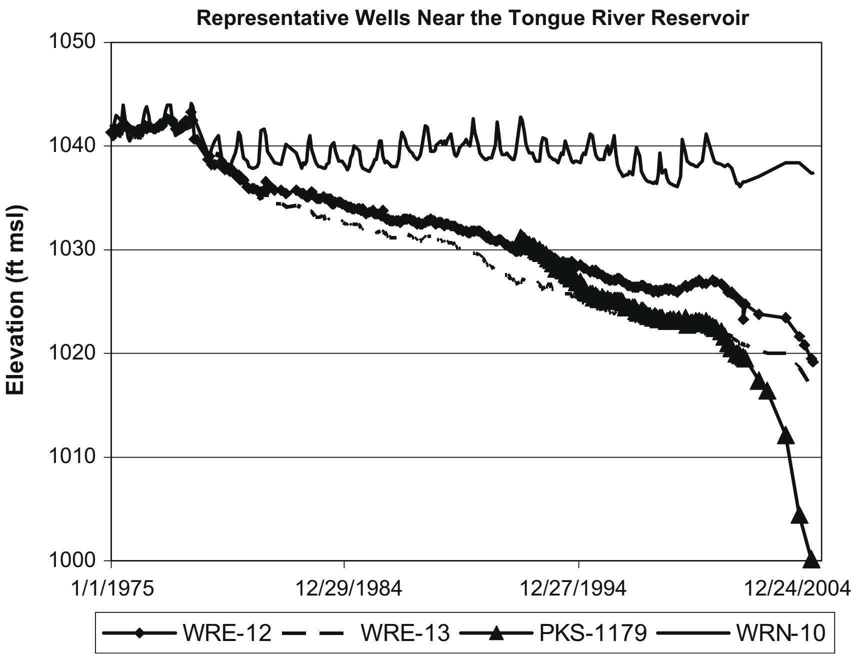

Fig. 7. Hydrographs of selected monitoring wells near the Tongue River reservoir. WRE-12 is 52 m deep screened in Anderson coal; WRE-13 is 63 m deep screened in Dietz coal; PKS-1179 is 86 m screened in Dietz coal; WRN-10 is 24 m deep in Dietz coal. See Fig. 5 for their location.

estimate the impacts of future CBM development at locations distant from the current development and to consider the effect of hypothetical reinjection scenarios (Myers, 2006). The model simulates steady state inflow as recharge throughout the basin and groundwater flow from Wyoming and outflow as discharge to springs, streams, and out-of-the-model domain to the north to the Yellowstone River. The scale is regional, and the model does not include perched aquifers or existing pumpage. Additional recharge occurs in certain areas as seepage from streams.

In transient mode, the model includes induced and seasonal stresses as may occur in the model domain due to CBM development, a massive new stress applied to the coal seam aquifers. The stress changes continuously with time throughout the period of CBM production, assumed to be 20 years, because the pumping rate changes to maintain the potentiometric surface about 5 m above the top of the coal seam. The model simulates the change in the potentiometric surface for the various layers due to CBM development and the subsequent changes in discharge to springs

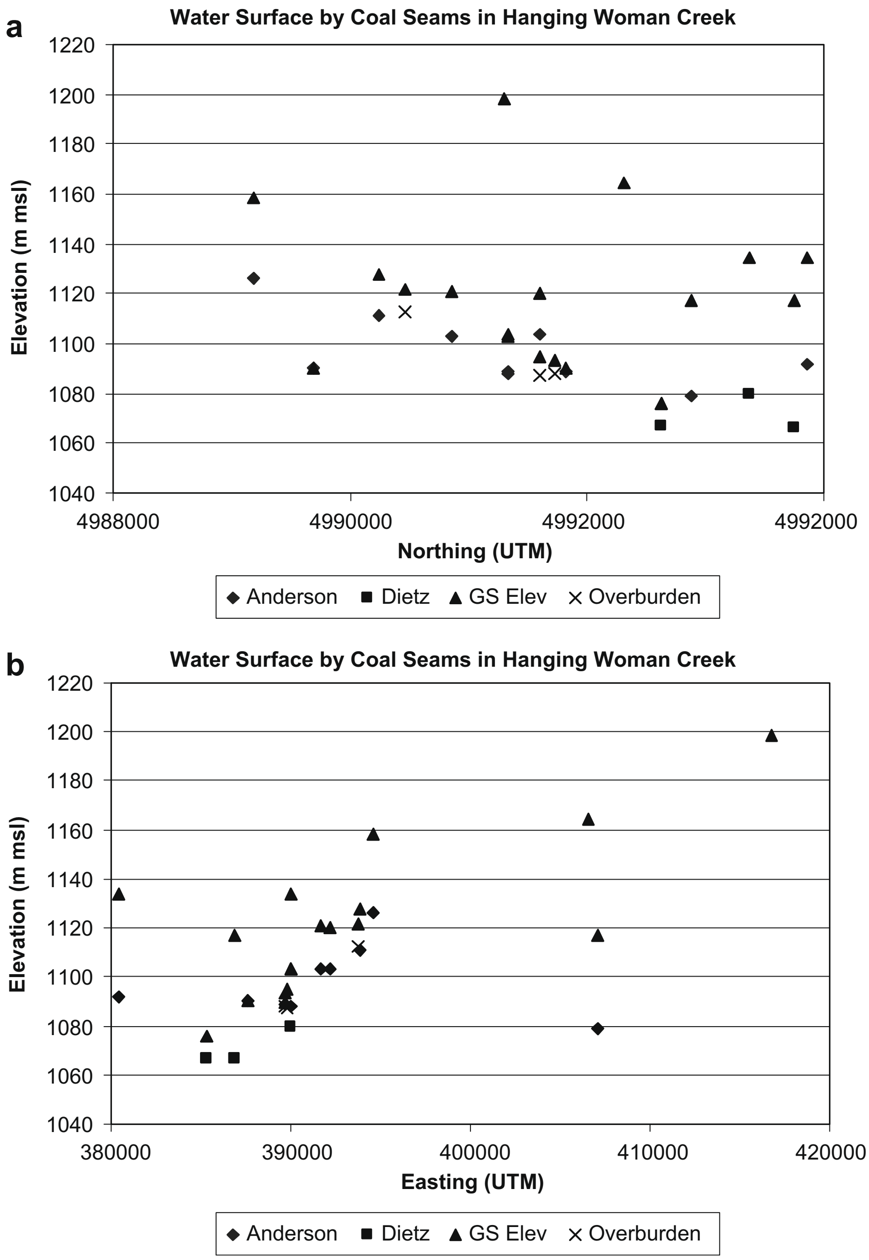

Fig. 8. (a) North-south water surface elevation trends for the Anderson and Dietz coal seams, the overburden layer and the ground surface (GS) elevation. (b) East–west water surface elevation trends for the Anderson and Dietz coal seams, the overburden layer and the ground surface (GS) elevation.

and streams. Development is simulated based on the best available estimate of sections projected to be developed (Fig. 1).

The model design employed the concept of parsimony balancing the desired precision and the sparse knowledge of the geology (Anderson and Woessner, 1992). Grid design balanced the need for computational efficiency around stressed cells with the lack of precise knowledge of the geologic layers. Coal bed methane pumping causes substantial drawdown over large areas within the well fields; therefore, these areas, simulated as drains (Fig. 9 and Transient simulation of CBM development) were discretized to 0.8 km squares. Nine layers were used to model the stratified geology. Layer 1 is the top of the model and represents both the Fort Union and Wasatch formation outcrops. The top elevation was based on the average elevation within the cells. Layers 2, 4, 6, and 8 are coal seam layers 9.1, 7.6, 15.2, and 15.2 m thick, respectively. The Anderson/Dietz, Canyon, Carney, and Knobloch coal seams were included. There are up to ten potentially developable coal seams, therefore, the coal seam layers analyzed herein should be considered generically. Intervening layers were sandstone or other sedimentary rock with a thickness depending on the elevations of the coal seams. Coal seam elevations were based on well logs and geologic cross-sections (Roberts et al., 1999). Layer 9 represents the underburden, which consists of various materials including deep sedimentary layers such as the Madison aquifer (Downey, 1984).

Each model layer extends to the outcrop of the seam that occur as the ground surface becomes lower north in the PRB. The layer edges, the point where the layers become unsaturated, are no-flow boundaries. Faults shown in Roberts et al. (1999) and Wheaton and

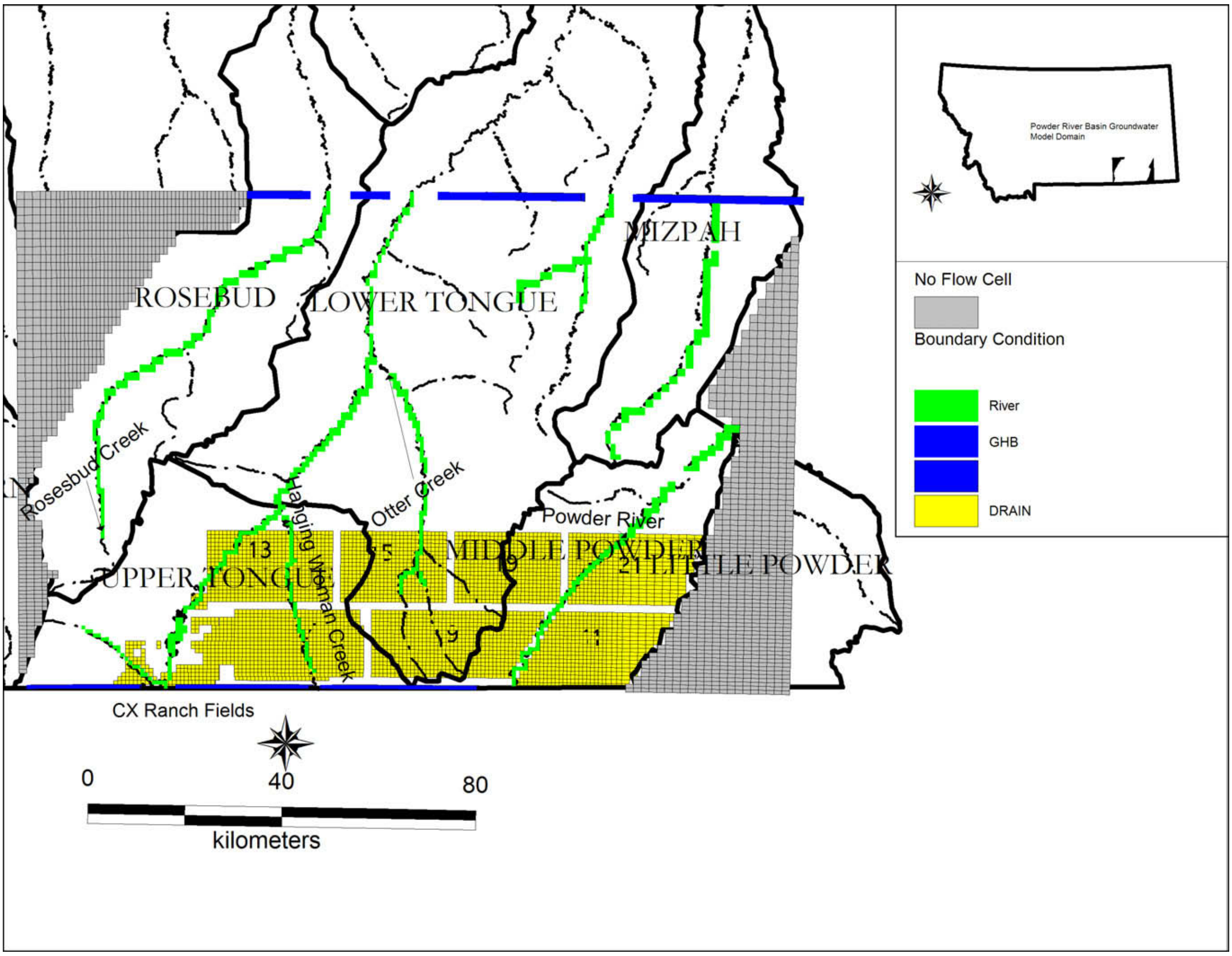

Fig. 9. Powder River Basin with the model domain and boundaries. Drain boundaries are used to simulate CBM development in transient mode. The general head boundary, (GHB) on the north is steady state for flow out of the domain. The GHB on the south represents inflow from Wyoming (AHA and Greystone, 2002).

Metesh (2002) were included in layers 2 through 9 if supported by hydrologic data.

Rivers were modeled with the RIVER boundary package (Fig. 9) (McDonald and Harbaugh, 1988). As a head-dependent flux boundary, this boundary condition allows an interchange of flow between the groundwater and surface water. General head boundaries (GHB), also head-dependent flux boundaries, controlled the flux to and from Wyoming on the south in all layers and toward the Yellowstone River on the north in layers 7 through 9. All layers have GHBs in the south; layers 7 through 9 have GHBs on the north. The GHB on the south was set to equal pre-development water levels as reported in AHA and Greystone (2002) for steady state conditions. The GHB package uses a parameter, distance to the location where the water level is specified, which was set equal to 6100 m. Setting the parameter a substantial distance from the actual boundary allows the simulated water level at the boundary to fluctuate. The RIVER and GHB boundary conditions influence the head but their fluxes must approximate water budget values.

Recharge is a specified flux boundary applied to the highest active model layer. Total recharge approximated 7.6 mm/y across the individual basins with some additional recharge along the ridges as needed to represent additional recharge through clinker zones.

Formation properties including conductivity and storage coefficients were specified using parameter zones based on stratigraphy and the conceptual model of the basins. Layers were subdivided into zones to implement the conceptual model (Fig. 10a and b).

Steady state calibration

Model parameters were adjusted in steady state to match computed water levels and fluxes to observed static water levels and expected fluxes. Observed and modeled head values matched well without trend among levels (Fig. 11). The mean, median, and standard deviation of the residuals are −1.2, −1, and 12.2 m, respectively, and the proportion that the standard deviation is of the range in observed head is 5.6%. Within 0.8 km square cells, a 2% gradient is more than 30 m over two cells. Considering faults, residuals up to 60 m are reasonable in a model of this scale if they average close to zero and if the water balance components are reasonable. Residuals were sufficiently small for the scale and purpose of modeling being completed here (Reilly and Harbaugh, 2004). Most of the larger positive residuals occur in the eastern part of the domain, especially in the headwaters of Otter Creek (Fig. 3), where observed data is sparse and the problems choosing observation wells are manifest.

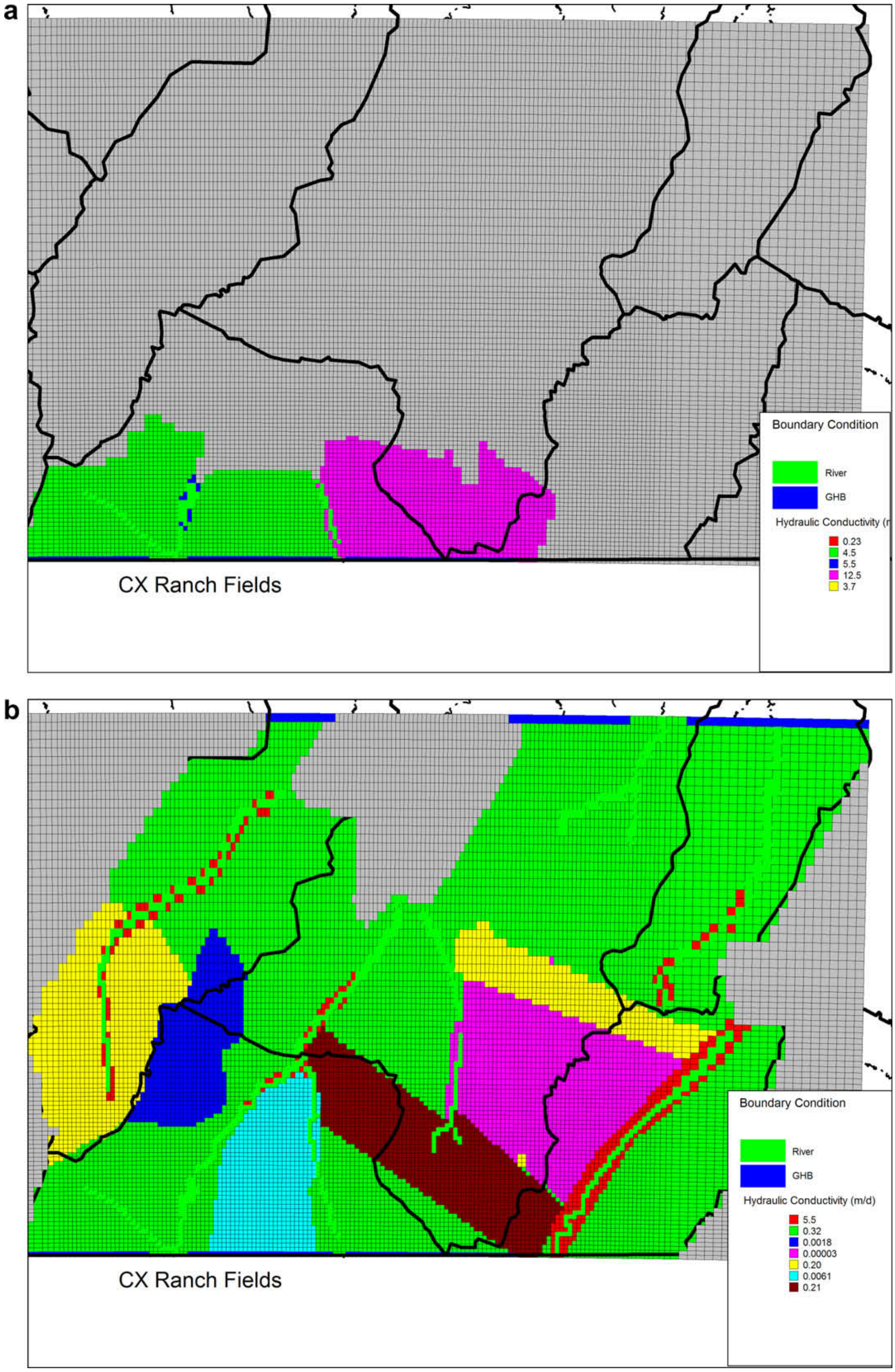

Fig. 10. (a) Hydraulic conductivity values and boundaries for layer 4, a layer that represents the Knobloch coal. (b) Hydraulic conductivity values and boundaries for layer 7, a layer that represents an interburden layer.

Horizontal and vertical conductivity and boundary condition conductance were initially adjusted using trial and error. To aid the calibration, sensitivity analysis using an autosensitivity analysis in which values were adjusted independently and the sensitivity for all parameters using the sensitivity routine within MODFLOW-2000 (Harbaugh et al., 2000) was completed. Conduc-

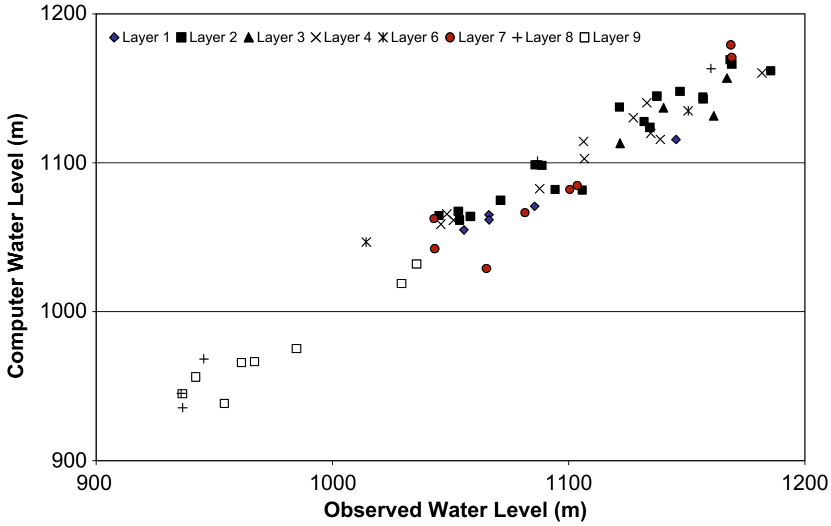

Fig. 11. Computed and observed water levels for the Powder River Basin steady state model calibration.

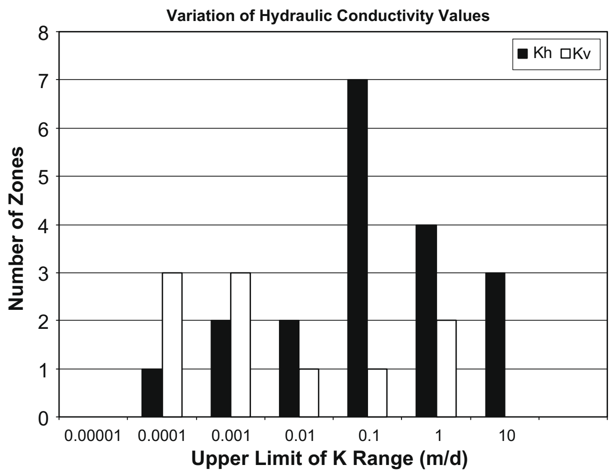

Fig. 12. Variation of hydraulic and vertical conductivity for model domain.

Table 2
Simulated steady state and measured fluxes for select model boundaries.

Boundary	Simulated flux (cms)	Observed flux (cms)
Recharge	3.24	
Net Boundary Flow	0.06	
Squirrel Creek	0.02	0.02
Tongue River	−1.45	−0.7
Tongue River Reservoir	−0.08	
Hanging Woman Creek	−0.09	
Pumpkin Creek	−0.17	
Rosebud Creek	−0.41	
Mizpah Creek	−0.03	
Otter Creek	−0.21	
Powder River	−0.89	−0.7

See Fig. 3 for the location of these streams. Boundaries without an observed flux do not have a representative measured flux.

tivity values were adjusted to lower the residual statistics. The final values had a wide range but most horizontal conductivity values exceeded 0.01 m/d (Fig. 12). The interburden layers have the lowest and the alluvium near the rivers have the highest values. The range for coal was from 0.2 to 4.5 m/d, a relatively small range compared to the ranges for interburden, which matches well the literature values discussed above. Coal vertical anisotropy ranged from 1.8 to 200, a small range compared to the interburden presumably because coal layers simulate one formation type and the interburden model layers simulate several formation layers.

Recharge in the headwaters of Squirrel Creek, Hanging Woman basin, and the ridge west of the middle section of the Powder River (Fig. 3), was increased to 22 mm/y to raise the potentiometric surface without setting the conductivity unrealistically low and to increase the discharge to Squirrel Creek.

Steady state water balance

According to the conceptual model, small rivers recharge aquifers at high elevation and large rivers receive groundwater discharge at low elevations. Rivers modeled as a river boundary accurately reproduced that conceptualization and the simulated flux values approximated measured and assumed rates (Table 2). For example, Squirrel Creek recharges the aquifer at an average rate of about 0.02 m^3/s (Table 2). The upper reaches of Rosebud, Otter, and Pumpkin creeks recharge the groundwater while their lower reaches gain flow from aquifer discharge. Their net flux is negative because the streams receive more discharge than they lose in recharge, which makes the streams a net sink for the aquifer system.

Measured river flow reported in Table 2 does not include shallow alluvial flow and losses to phreatophytic vegetation. However, the modeled discharge does include these losses because the model does not simulate the local processes near the streams. Therefore, the discharge should exceed the measured changes in river baseflow. For example, the 0.41 m^3/s net groundwater discharge to Rosebud Creek may appear high, but it occurs over 96 km of stream with a riparian zone supported with groundwater from the alluvium and the discharge from the model domain. With observed baseflow on the Tongue River ranging from 5.7 to 6.5 m^3/s, the measured discharge to the river is 0.8 m^3/s. This compares favorably to the 1.45 m^3/s simulated discharge because both the river and aquifer discharges to the alluvium replenish bank storage lost during the growing season.

Total simulated steady state discharge to rivers equals 3.24 m^3/s or approximately the recharge plus the small amount of flow gained from the GHB boundaries, inflow and outflow to and from the model domain through the lateral boundaries, which nets about 2% of river flow (Table 2). The steady state water balance as simulated in this model accurately represents the water balance for flow through the PRB.

Transient calibration

CBM development lowers the potentiometric surface to about 4 m above the top of the coal seam at CBM wells. However, the shape of the potentiometric surface over a given area affected by a well complex is the sum of overlapping drawdown cones. To simulate water removal over a large area, the MODFLOW drain boundary routine was used to emulate a well field (Myers, 2006). The potentiometric surface within the drain cell was set to about 8 m above the top of the coal seam layer at the beginning of the period to reflect the overlapping drawdowns from individual wells (Myers, 2006).

Transient calibration involved adjusting drain cell conductance and aquifer storage properties. Drain cell conductance was set so that the observed pumping rates commenced at about 80 l/m per well and decreased to about 20 l/m after 2 years. The assumption is that a well field comes fully on-line at the beginning of a year, simulated with stress periods, two of which are 91 days long and the third 183 days. The time step multiplier is 1.2.

The expected drawdown after 6 months at a drain cell was set to be approximately half the total drawdown specified at the drain. After 90 days the drawdown was set to be approximately half the 6-month drawdown. The development period was 2000 through 2004 with drain cells becoming active according to the observed development scenario for a total of 15 stress periods.

Target drawdowns at points away from the fields were set hypothetically based on the observed changes discussed above. Actual wells were not used because detailed pumpage at nearby wells is not known and the screens of potential monitoring wells do not adequately match model layers. Based on observations at the CX Ranch field, at a 0.8 km radius, the layer 6 target drawdown was 30 and 70 m within 3 and 24 months, respectively. At 3.6 km, the target drawdown is about 12 m in 2 years. After 5 years, the 3-m drawdown should reach about 8 km from the development. In layer 4, the target drawdown is effectively halved for each time step. The drawdown in the interburden, layer 5, should be about half of that within the coal seam layers. Layer 8 was not developed at the CX Ranch.

The storage coefficients were adjusted so that the drawdown approximated these specified values. The calibrated specific storage for the interburden layers 5 and 7 was $1 \times 10^{-6}\ m^{-1}$. For layer 3, it was $2 \times 10^{-6}\ m^{-1}$. For coal seam layers, it is 9×10^{-4}, 3.8×10^{-6}, 5×10^{-6}, and $3 \times 10^{-7}\ m^{-1}$, for layers 2, 4, 6, and 8, respec-

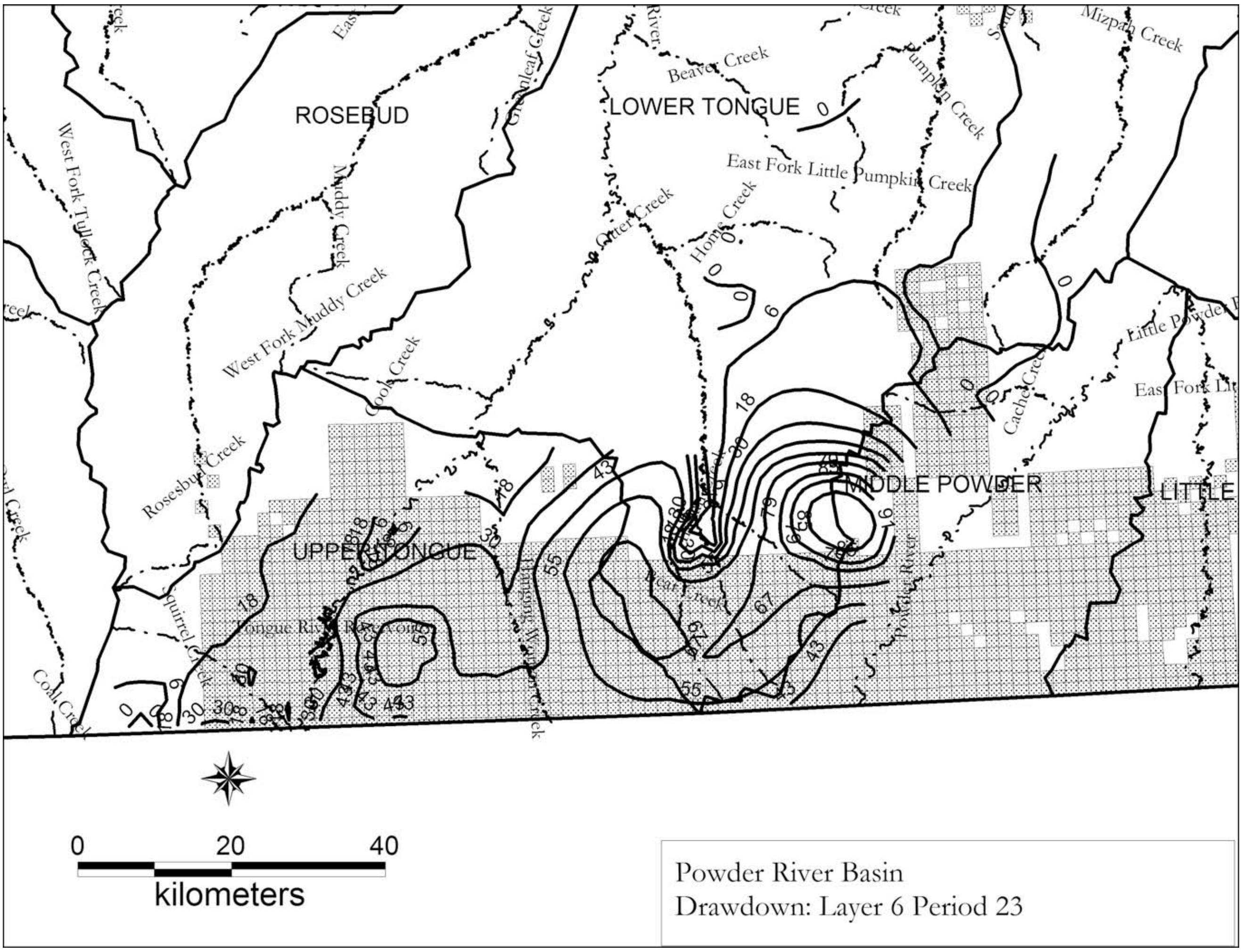

Fig. 13. Simulated drawdown after 23 years, at the cessation of CBM pumping in the west and the beginning of pumping in the east. Drawdown shown for model layer 6, the Knobloch coal.

tively. These values decrease with depth because of the overburden pressure. The porosity of all coal seam layers is 0.02. Specific yield of layer 1 is 0.1. The specific yield of alluvial aquifers is 0.2.

Transient simulation of CBM development

Full CBM development in Montana began at the CX Ranch and will proceed eastward and northward over a 20-year period from the start of development (Fig. 1); the groundwater modeling simulated the development in a realistic fashion. The modeling included 20 years of project development with up to 15 years of pumpage for each field. For all simulated fields, pumping commenced within the first 20 years and continued for up to an additional 15 years, depending on the layer. All model coal seam layers were simulated to be developed. For the current fields, the actually developed seams were simulated. The drain boundaries simulated pumping for 9, 11, 13, and 15 years for layers 2, 4, 6, and 8, respectively, which simulates the shallower seams being depleted sooner. The modeling used 40 one-year-long periods simulating well-field development and production followed by 10 recovery periods: 1, 4, 5, 10, 10, 10, 10, 20, 30, and 100 years long. Each 0.8 km square drain cell simulates 2 wells per layer. With approximately 7700 drain cells, the model simulated 15,000 CBM wells.

Artificial recharge (Huisman and Olsthoorn, 1983) was simulated by returning water removed from a drain cell to other cells in the domain using the methods of the drain return package in MODFLOW-2000 (Banta, 2000; Harbaugh et al., 2000). Water withdrawn from the deeper coal seams, model layers 6 and 8, was placed into previously depleted coal seams and interburden. Specifically, water withdrawn from the fields on the east side of the modeled CBM development was injected into coal seams and interburden that had previously been depleted, mostly on the west side of the study area (Fig. 8) mostly between the Tongue River and Hanging Woman Creek (Fig. 3). Reinjection can occur only after pumping has ceased, which limits the opportunities. Fifty percent of the water pumped during a period that reinjection was possible was placed as return flow in the receiving coal seam. Most of the reinjected water was placed into upper layers because these layers recovered more slowly and have the most immediate effect on river flows. A small amount of water was returned to layer-1 cells along Otter Creek, Hanging Woman Creek, Powder River, and Tongue River (Fig. 3) to simulate rapid infiltration basins.

Results of analysis

Full-scale development

CBM fields commence development at variable times, which causes maximum drawdown and extent to vary across the area (Figs. 13 and 14). The maximum drawdown at some well fields may occur before other fields have commenced pumping. Draw-

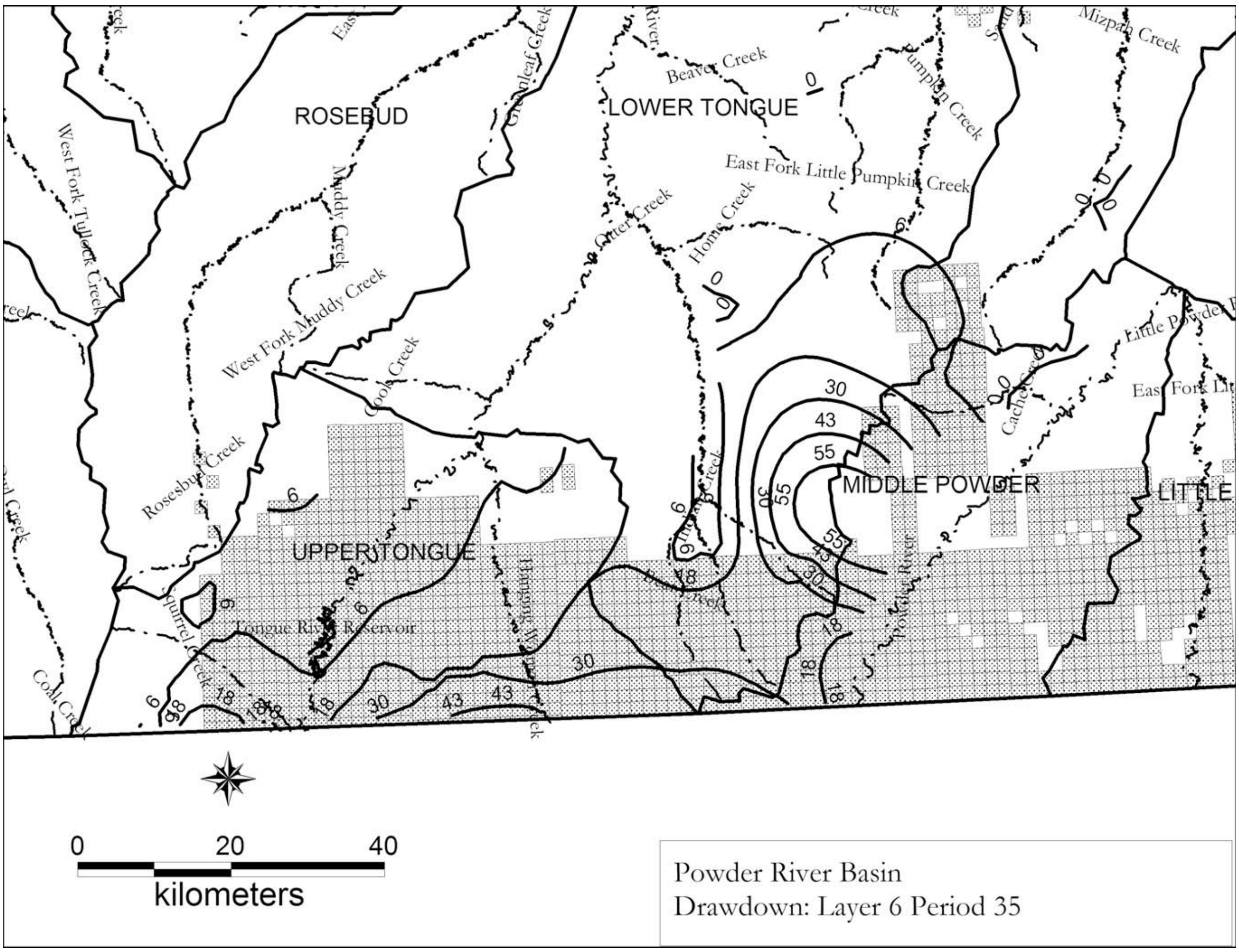

Fig. 14. Simulated drawdown after 35 years, at the cessation of CBM pumping in the east. Drawdown shown for model layer 6, the Knobloch coal.

down expands with recovery at the fields and may overlap with drawdown from new fields just being developed.

Maximum drawdown occurs in the deeper layers. Drawdown is higher near outcrops because the outcrops are no-flow boundaries causing there to be little water available to replenish the pumping. Seepage limits the drawdown near rivers; for example, this reflects the observed hydraulic connection along the Tongue River.

Recovery from pumping occurs by redistributing the water stored in the aquifers and by diverting recharge from its natural point of discharge to the area of deficit (Theis, 1940). It draws groundwater from a distance that spreads the deficit across a much larger area until it is replenished by replacing discharge to other natural discharge points such as springs and streams. To return to close to pre-existing water balance conditions, the natural discharge must be decreased (Bredehoeft, 2002).

Recovery in the middle of the fields occurs relatively quickly due to the steep gradient existing upon the cessation of pumping (Figs. 14 and 15). Just 5 years after pumping ceases in the CX Ranch area or the fields between the Tongue River and Hanging Woman Creek, the drawdown has substantially recovered (Fig. 16). Considering 6-m contours, recovery 15 years after pumping ceases is complete except for on the east side of the domain (Fig. 15). The continuing 12-m drawdown occurs on a mountainous area where the initial water levels had been a groundwater divide. Drawdown also continues along the Wyoming border due to residual drawdown in Wyoming (Fig. 15).

Layer 8 recovered more quickly than shallower layers, 6 and 4, respectively, even though it has more drawdown at the end of pumping (Fig. 16) for three reasons. First, a steeper gradient exists in deeper layers because CBM pumping lowered the head further due to the depth of the layer. Second, the deeper layer has a lower storage coefficient which means the coal requires less water for a given water level recovery. Third, there is less horizontal constraint in the deeper layers because the CBM development is further from coal outcrops. Shallow aquifers recover more slowly in regions not close to a river because they are limited by low recharge so recovery requires upward flow from lower layers, which is limited by low vertical conductivity.

Over 40 years, full CBM development will pump about 124,000 ha-m of water from the Fort Union coals and interburden in the PRB, or about 36% of the total recharge simulated for the entire model domain. Initial simulated pumpage rates for each drain cell (assuming two wells per cell) varied from about 136 l/m to less than 8 l/m, which reflects the different properties and water levels near the drain cells. Simulated pumping rates are slightly lower than expected by the industry (ALL, 2001) because the model commences all pumping in a field simultaneously and does not account for localized areas without wells. The lowest pumping rates occur where required drawdown is low or where nearby fields had already caused drawdown.

About 55,500 ha-m will be removed from storage by pumping in 40 years. Almost-full recovery will require more than 200 years, but residual storage depletion is not obvious on maps because

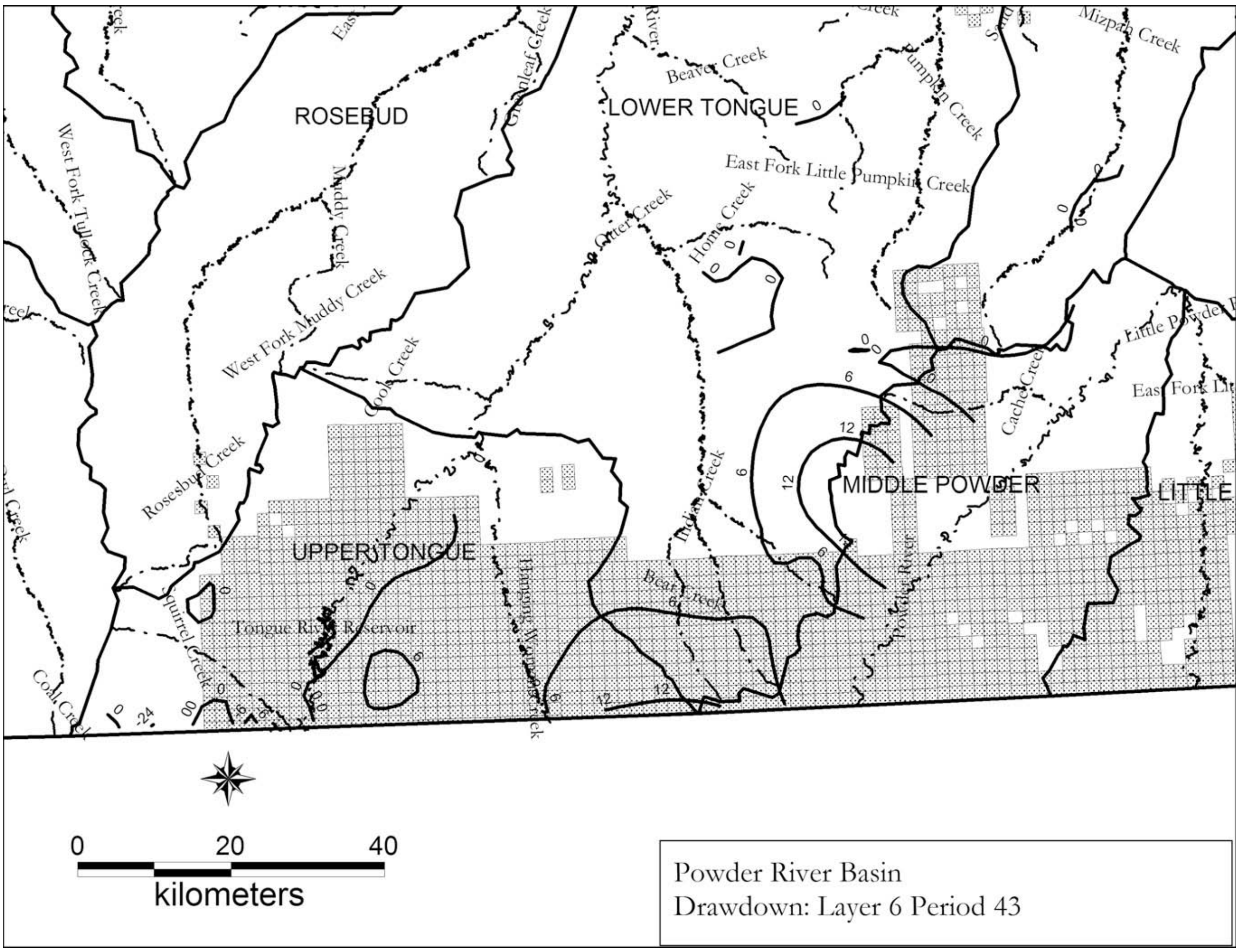

Fig. 15. Simulated drawdown after 50 years, 15 years after the cessation of CBM pumping in the east. Drawdown shown for model layer 6, the Knobloch coal.

drawdown of only a meter or less occurs over a large portion of the PRB.

Coal bed methane pumpage affects the flow to the nearby rivers with total river flux dropping by almost half at its most extreme (Fig. 17). The flow to Hanging Woman Creek decreases from 0.17 m^3/s discharging to the river to almost 0.03 m^3/s being drawn from it (Fig. 17). Hanging Woman Creek may be the most affected because there will be nearby development for most of the development period.

Between the 4th and 90th year, total inflow to the Tongue River Reservoir decreases by 5440 ha-m. After the 90th year, or 55 years after CBM development ceases, the flux to the reservoir has recovered to the pre-development levels. This flux decrease reflects the conceptualization of a hydraulic connection discussed above.

Coal bed methane development also affects springs and wells. The maximum extent of a drawdown cone occurs at differing times depending on the CBM development schedule and the varying recovery rates around the CBM fields. The shallow portions of the drawdown cone will continue to expand even as the nadir of the cone begins to rapidly recover. The maximum extent of the 0.3 and 6-m drawdown contours eventually encompasses 781 springs and 1890 wells, respectively. Many of these could be affected by CBM development at some point during the development or recovery period.

Development with artificial recharge

The reinjection scenario saved about 4070 ha-m of groundwater over the life of the development. Approximately 10% of the lost flux to rivers was saved (Fig. 18). In layer 6, 5 years after pumping ceases the drawdown cone shape is similar to that for development without reinjection (Fig. 14), but the contours are contracted by from 3.2 to 6.4 km, or the area affected by a given drawdown is up to 20% smaller. In layer 8, reinjection contracts the 12-m drawdown by about 12.8 km. Similar reductions in the extent of drawdown were observed in other layers. Full recovery occurs about 10 years earlier with reinjection, although some of the reinjected water flowed south to Wyoming. The reality is that reinjection will cause the water level to recover more quickly than modeled.

Conclusion

CBM development has and will continue to deplete groundwater in the southern portion of the PRB in Montana. It will remove a large proportion of the natural recharge and decrease the groundwater discharge to rivers. Discharge to the rivers, on average, will decrease about 25%. Drawdown may affect hundreds of wells, springs, and surface water rights because CBM pumpage equaled about 36% of modeled recharge, with about 44% of the pumpage being drawn from storage. The decreased storage slowly transfers

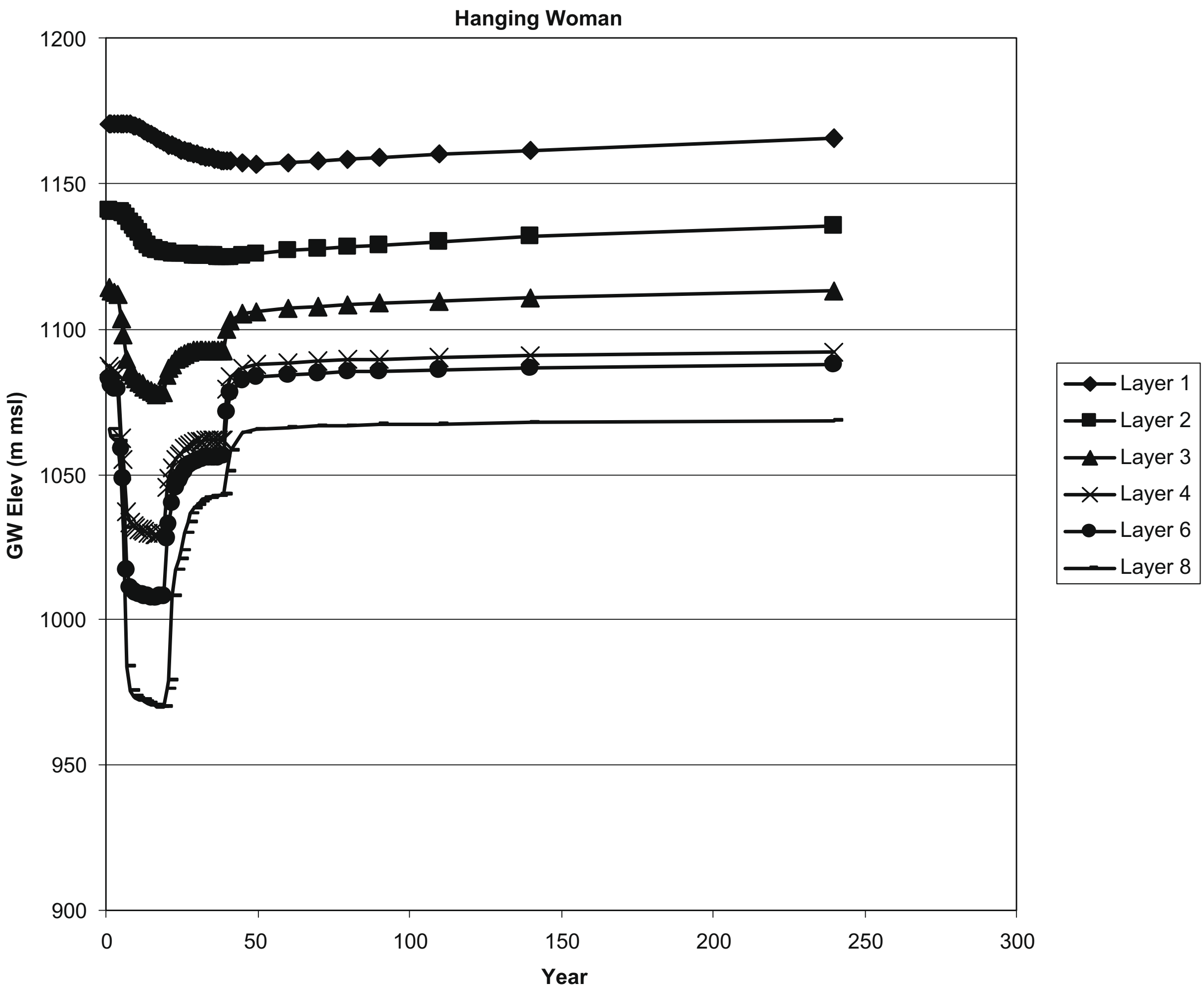

Fig. 16. Water level hydrographs for a hypothetical monitoring point midway between the Tongue River and Hanging Woman Creek (see Fig. 3) for model layers 1, 2, 3, 4, 6, and 8. Layers 2, 4, 6, and 8 represent coal seams. Layers 1 and 3 are overburden and interburden layers, respectively.

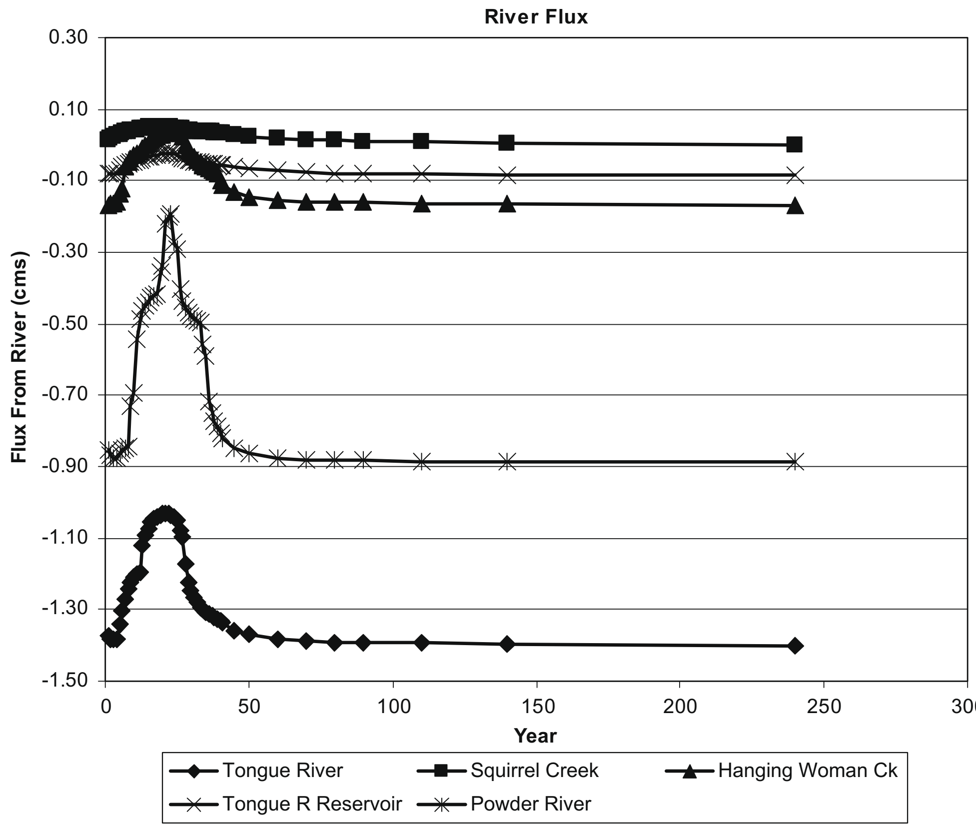

Fig. 17. Estimated river flux from various rivers. The value is negative if it represents flow to the river from the model domain.

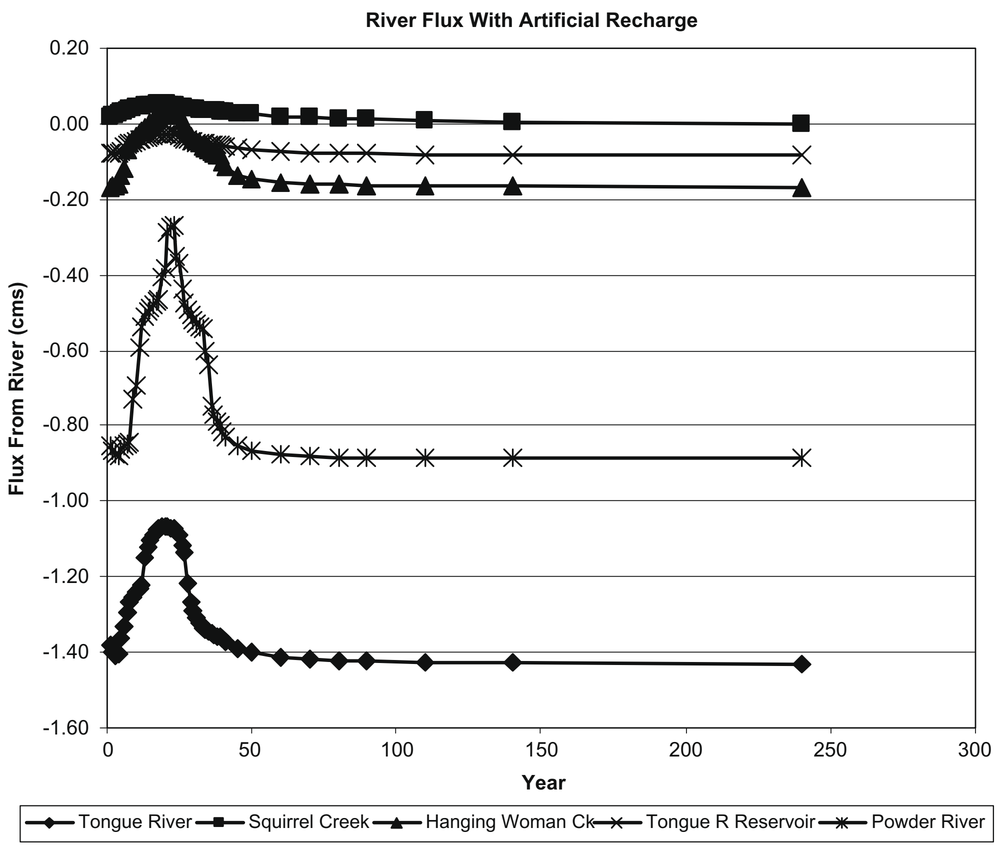

Fig. 18. Estimated river flux for the full development with reinjection scenario. The flux is negative because it is water subtracted from the model domain water balance. This should be considered flux to the alluvial aquifer near the river.

the effects to the river fluxes as natural discharges are displaced (Bredehoeft, 2002).

The drawdown and concomitant impacts last far beyond the end of CBM pumping, but the discharge over the long term was decreased only a few percent. The long-term effects are caused by replenishing the depleted storage. Recovery will require up to 50 years, although some effects of the depletion will occur for much longer.

CBM development impacts can be mitigated in two ways. First, reinjecting produced water into depleted coal seams would replenish the lost storage so that recovery would draw less groundwater from long distances. Second, rapid infiltration basins near potentially-affected rivers could decrease the short-term river flow depletion, but they should only be used if the water quality will not degrade the river water (Wang et al., 2007).

Requirements of the MODFLOW drain package (Banta, 2000) hampered reinjection planning for the scenario considered here. A limitation is that only fields that had ceased pumping could receive production water. Another limitation is that reinjection can only occur for an entire modeled period, not commence in the middle of the simulation, which would make it possible to simulate more reinjection. A longer development and pumping scenario would provide for less overlap among development regions and increase the potential for reinjection into depleted fields. Also, it might be desirable to reinject water in upper layers while producing the lower layers, a scenario that cannot be modeled with the current drain return package (Banta, 2000).

Reinjection and artificial recharge (Huisman and Olsthoorn, 1983) could mitigate some hydrologic impacts of CBM development. The storage depletion would be lessened and the rivers would not lose as much groundwater inflow. Extending the period of development would increase the opportunities for reinjection and decrease the negative impacts of CBM-induced drawdown.

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