ASSESSING THE CUMULATIVE IMPACTS OF SURFACE MINING AND COAL BED METHANE DEVELOPMENT ON SHALLOW AQUIFERS IN THE POWDER RIVER BASIN, WYOMING[1]

by

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Abstract: Large scale surface coal mining taken place along the cropline of the Wyodak-Anderson coal seam since approximately 1977. Groundwater impacts due to surface mining of coal and other energy-related development is a primary regulatory concern and an identified Office of Surface Mining deficiency in the Wyoming coal program. The modeled aquifers are the upper unit (coal) of the Paleocene Fort Union Formation and the overlying Eocene Wasatch Formation. A regional groundwater model covering 790 square miles was constructed using MODFLOW, to simulate the impacts from three surface coal mines and coal bed methane development occurring downdip. Assessing anisotropy of the coal aquifer, quality checking of *in situ* aquifer tests and database quality control were precursors to modelling. Geologic data was kriged to develop the structural model of the aquifers. A Geographic Information System (GIS) was utilized to facilitate storage, analysis, display, development of input modelling arrays and assessment of hydrologic boundaries. Model output presents the predicted impacts of likely development scenarios, including impacts from coal bed methane development and surface coal mining through anticipated life of mining, and surface mining impacts independent of gas development.

Additional Key Words: Groundwater Modelling, Cumulative Impact Assessments, MODFLOW, GIS

Introduction

General Setting

Location. The study area is located within the Little Thunder Creek Drainage in the Powder River Basin of northeastern Wyoming. The drainage is underlain by significant minable coal reserves currently being extracted by three active surface mines. Coal bed methane (CBM) development has been recently proposed west of, and structurally downdip from, the surface coal mines. The study area is located in the ephemeral Little Thunder Creek drainage. Little Thunder Creek is tributary to Black Thunder Creek, which in turn meets the Cheyenne River near Hampshire, Wyoming. The area is sparsely populated. The closest town is Wright, WY (population 1300), eight miles west of the Black Thunder Mine permit boundary. Gillette, Wyoming is approximately 50 miles north of Black Thunder Mine on highway 59 (Figure 1).

Geology. The uppermost sequences of the Tongue River Member of the Fort Union Formation have thick, commercially valuable coals and coal zones. These coals are of relatively low rank (subbituminous B-C), and have been mined commercially using surface mining methods since the mid 1970s, with mining activity accelerating since the mid-1980s.

A low permeability unit underlies the coal and acts as a confining layer. The Eocene Wasatch Formation overlies the Fort Union Formation and contains lenticular sand and shale sequences, and thinly-bedded coals. The first encountered groundwater is generally from these Wasatch Formation sand lenses. Wasatch Formation well yields are highly variable, depending on the areal extent of the water-bearing formation. The primary use of Wasatch formation water is for stock wells with isolated potable water users (Lewis and Hotchkiss, 1981). The coal aquifers are also primarily used for stock water.

Groundwater Modeling

Modeling of groundwater flow in the Little Thunder Creek drainage was undertaken in response to the finding of need for a Cumulative Impact Assessment in the area. The need was established in response to the Office of Surface Mining finding of deficiency in the State of Wyoming Coal permitting process with regard to Cumulative Hydrologic Impact Assessments (CHIA)

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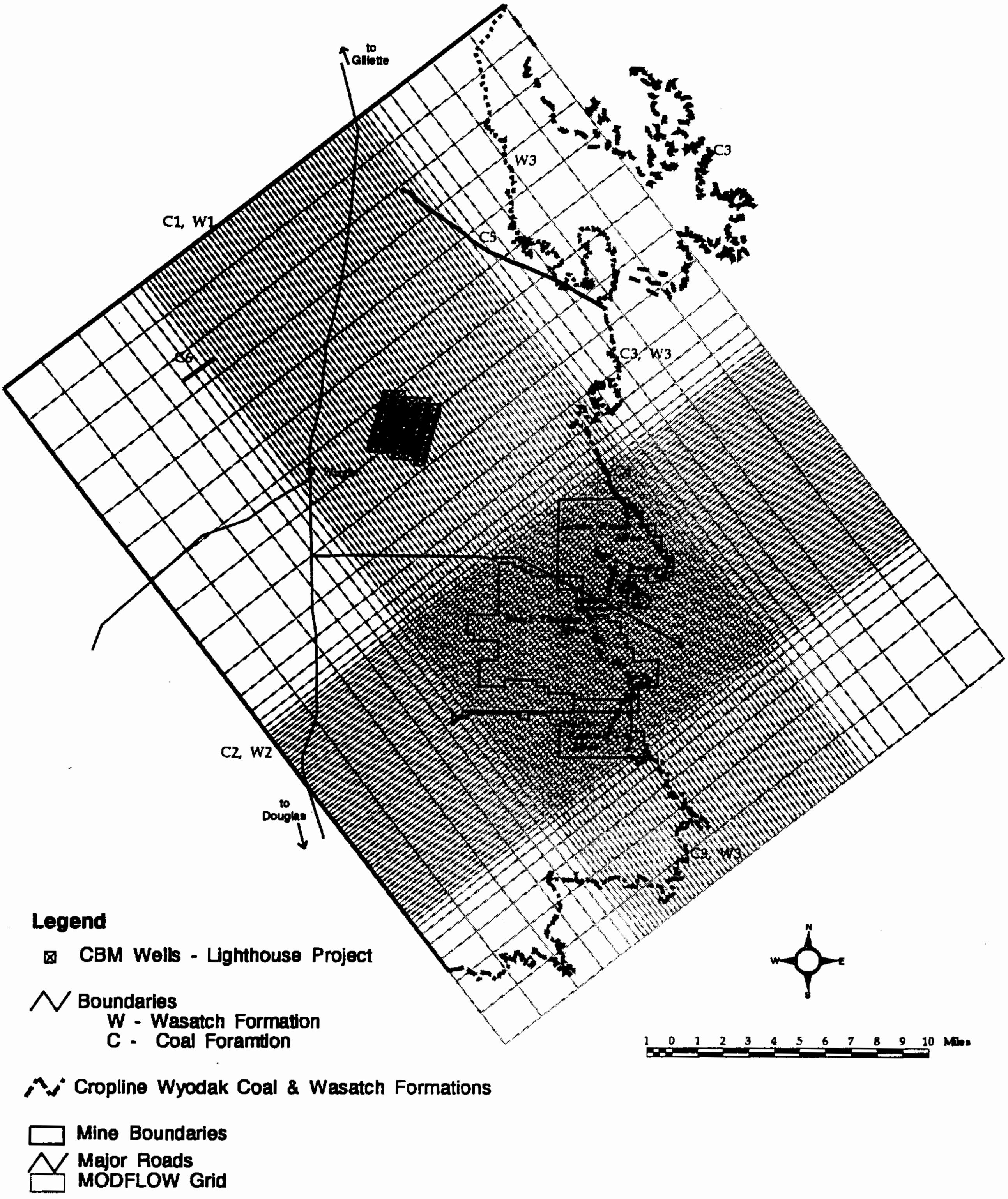

Figure 1. Model domain layout, showing grid, hydraulic boundaries and stress locations.

for surface coal mining.

Groundwater flow impacts are expected to the upper Paleocene Fort Union Formation sequences, and to the Eocene Wasatch Formation as a result of surface mining and of coal bed methane development. Both industries are regulated independently, with separate groundwater compliance requirements, and to date their cumulative impacts have not been considered.

Objectives. The specific objectives of the present modeling efforts are as follows:

- Model aquifer stresses to the Wyodak Coal (upper Fort Union Formation) and the Wasatch Formation under two development scenarios:

  1. Considering only historic and future surface mining;

and

  2. Considering both surface mining and CBM development.

- Provide a dynamic tool for regulatory agencies to assess the likelihood of material damage from current and future energy development;

- Provide an initial quantification of the recharge dynamics at the coal - clinker interface;

Conceptual Model

Aquifer System-General Discussion

The stratigraphic column of the Powder River Basin shows the Wasatch Formation overlying the Ft Union formation in the study area. Geologic nomenclature for the coal seams in the area differ. For the purposes of this report, the top unit of the Ft. Union formation will be called the Wyodak coal.

Range fires and lightning strikes have ignited areas of exposed coal at the land surface. Burning following ignition has subsequently formed clinker deposits. Clinker is highly permeable, and has become saturated from infiltration of precipitation and snowmelt. 'Ponding' of water may occur where clinker meets the less permeable coal and sediments of the Wasatch and Fort Union Formation (Heffern et al, 1996). Previous investigations have treated this boundary as a recharge boundary for the coal (Western Water Consultants, 1994; Lower, 1992) (Figure 2).

Groundwater flow is generally to the northwest (downdip) in the Powder River Basin (Daddow, 1986). Premine data indicates that hydraulic gradients for the Clinker/Wasatch/Coal are steep near the cropline with highest potentials in the clinker. Near-cropline flow patterns are complex, with local flow patterns dominating. Premine potentiometric surfaces at Jacobs Ranch and North Rochelle Mines indicate that the hydraulic gradient is greater in this vicinity. Downdip data are sparse to nonexistent, a deficiency of the available data.

Recharge occurs from two sources: (1) Precipitation (a minimal source of recharge to the Wasatch Formation due to arid climate); and (2) the clinker contact with the coal aquifer and the Wasatch sediments on the east side of the model area.

Hydrologic Boundaries

The Coal/Clinker/Wasatch boundary is modeled in this report as a semi-permeable boundary. A unit of porous material, in this case the coal and the Wasatch formation, are in contact with another porous material domain (the clinker) through a semi-pervious boundary (zone of alteration) (Gerlach, 1995; Heffern et al 1996) (Figure 2).

Lineaments. Denson et al (1980) mapped several lineaments in the study area from surficial features. Where these features correalted to subsurface structure in the Wyodak coal, augmented hydraulic conductivity zones were modeled in the coal.

Faults. Faults frequently act as impermeable boundaries due to aquifer offset. Denson et al (1980), and Mitchell and Rogers (1993) speculate on the existence of faults within the study area. Faults were investigated in model calibration.

Hydraulic Properties.

Initial values of hydraulic head for the coal, clinker and Wasatch Formation were needed model inputs as were storage coefficient, hydraulic conductivity, vertical hydraulic conductivity and anisotropy. Hydraulic parameters should approximate the best available data from aquifer tests. The coal aquifer is modeled as an anisotropic medium. Considerable literature indicates that flow is dominated by fractures associated with various formative processes (Close and Mavor, 1991; La Point and Ganow, 1986; Stoner, 1981)

Sources and Sinks

Point Sinks. The mining sequence was simulated as incremental impacts in one year stress periods from

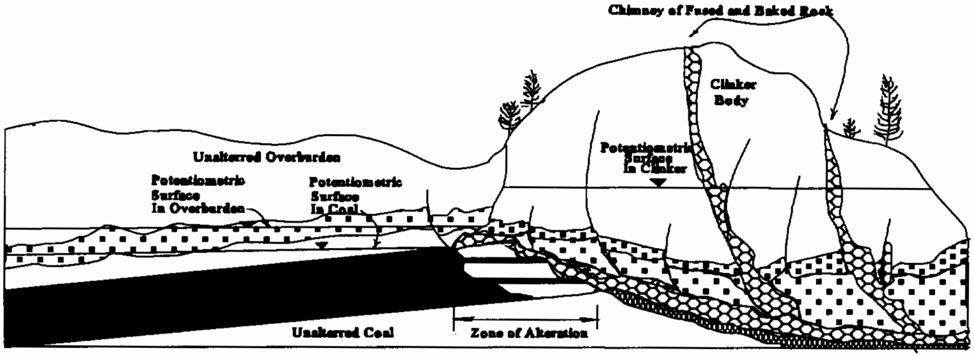

Figure 2. Geologic cross-section showing the spatial relationship of the coal, clinker, and overburden and the 'zone of alteration'.

1975 to present. Predictive simulation of impacts are modeled to the presently anticipated end of mining, year 2021 as of 1995. Gas production was simulated in the area using the development scenario proposed in the1995 NEPA document for the Lighthouse study (BLM, 1995). Mining impacts were modeled with and without CBM.

Distributed Sources. Distributed sources are limited to recharge to the top layer. This is included in the modeling scenario to simulate vertical recharge from precipitation and snowmelt. Precipitation in the Powder River Basin averages 10-16 in/year (Marston, 1990). Basin potential evapotranspiration exceeds precipitation, generating an annual negative net water balance.

Methods

Model Domain

The model domain is presented in Figure 1. The entire model grid covers 790 mi^2. Model spacing along rows varies from 8250 ft to 825 ft. The dimensions along columns varies from 9475 ft to 948 ft. The fully refined cells completely enclose the present permit boundaries of Jacobs Ranch, North Rochelle and Black Thunder mines.

Where stresses are imposed, it is desirable to minimize the distance between node centers to insure that nodes can be adequately represented in the flow system by a single hydraulic value.

Model Layering

Kriged grids of the four model surfaces were produced in GEOEAS. These surfaces were imported into ARC/INFO as point coverages, then exported as ARC/INFO lattices (grids). The ARC/INFO grids were interpolated to smaller grid spacing and assigned to model grid nodes using the ARC/INFO LATTICESPOT AND LATTICERESAMPLE utilities. The MODFLOW grid was developed in ARC using MODELGRID (Winkless and Kernodle, 1993). Final model arrays were output using MODARRAY (Winkless and Kernodle, 1992).

Hydraulic Parameters

Hydraulic Conductivity in the Central Powder River Basin. The permit to mine applications of nine mines in the Powder River Basin (including the three mines in the central study area) were examined, and all pump tests were extracted. All tests were examined and approximately 20 percent were reanalyzed. All tests were evaluated for reliability and rated from 0 to 3 (least to most reliable). A statistical analysis of the tests was conducted. Results are summarized in Table 1.

Discussion. Data were not excluded from analysis for any reason. Pump tests and slug tests were treated alike. Some wells were tested multiple times, and reanalysis contributed replicates. The clinker has the highest range (and variance) of all the data sets, although the Wasatch data is also highly variable. The low values of hydraulic conductivity for clinker were derived from slug and injection tests of short duration. The number of tests for the backfill is very small (N = 7). Any additional data would increase the reliability of backfill statistics.

Spatially, some tests are from mines out of the study area. Additionally, PTMA documentation reveals a significant degree of spatial variability between mines within the Little Thunder Creek area. This may be attributable to zones of enhanced permeability associated with lineaments or anticlines.

Hydraulic Conductivity in the Study Area. The 'Central Powder River Basin' data set was examined and the best available data within the study area were selected using the following criteria:

- Data were restricted to mines within the study area (Cordero, Coal Creek, Jacobs Ranch, Black Thunder and North Rochelle);
- Data were limited to tested wells in the Wyoming Department of Environmental Quality (WDEQ) Coal Permit and Reclamation (CPR) database;
- Aquifer test ratings assigned in the lab were restricted to 1, 2 and 3 only;
- Only one test was allowed per well.

The 'quality-checked' data was used to choose a 'mean' or best initial approximation of aquifer hydraulics for the model area. All deterministic calibration/verification adjustments were then made to this initial condition. A summary of the quality checked data is presented in Table 2.

Discussion. Sample size is restricted when data is subject to location, quality and replication criteria. The two aquifer tests within the study area for the backfill were from the same well and were rated least reliable (0). Study area data for the Wasatch Formation shows hydraulic conductivity ranging from .133 to 1.33 ft/day, indicating generally low permeabilities with low variability.

The study area data indicates that the clinker is a highly permeable aquifer. It is also a difficult aquifer to test, with long-duration, high-yielding tests a necessity due to the high permeabilities. Coal aquifer hydraulic conductivities are higher than the 'Central Powder River Basin' data set, and remain log-normally distributed.

Model Hydraulic Conductivity Inputs. Model hydraulic conductivity inputs for the Wasatch Formation, coal, and clinker aquifers are presented in table 3. Wasatch formation aquifer testing was limited to eight tests in the study area (Table 2). The data for the these tests indicates low variability in hydraulic conductivity. The reported values of hydraulic conductivity for the Wasatch in Martin (1988) were used in the model, with sensitivity analysis on this input.

Hydraulic conductivity for the coal aquifer is based on the *in situ* values reported in table 2. Individual values of hydraulic conductivity were adjusted during calibration and verification to minimize RMS error.

General Head Boundary Conductance. The proposition that recharge along the Coal/Clinker/Wasatch boundary can be reduced to a quantifiable flux is dependent on (1) *A priori* knowledge of the flux from testing; or (2) an accurate conceptualization and spatial description of hydraulic conductivity between the clinker and recharged aquifers.

Given that the boundary flux is unknown from *in situ* testing, it may be approximated using the following modeling technique using the MODFLOW

Table 1. Summary statistics of hydraulic conductivity for 274 aquifer hydraulic tests in four aquifers in the Central Powder River Basin.

Aquifer	Number of tests in Central PRB Area	Mean K (ft/day)	Median K (ft/day)	Mean of log transformed K (ft/day)	Variance
Coal	166	119	1.47	0.4934	3.822
Clinker	15	10061	104.26	5.727	16.11
Wasatch	86	3251	0.401	0.288	11.7
Backfill	7	5.82	0.134	-0.54432	5.37

Table 2. Summary statistics of quality checked hydraulic conductivity data within the Pilot Study. N.D indicates that no data satisfied the quality checking criteria.

Aquifer	No. Tests in Pilot Study Area	Mean K (ft/day)	Range K (ft/day)	Mean of log transformed (K) (ft/day)	Variance of logs
Coal	38	7.91	.133-79.40	1.26	1.72
Wasatch	8	0.62	.133-1.33	-0.789	0.226
Clinker	2	51000	50,000-52,000	10.84	0.006
Backfill	0	N.D.	N.D	N.D.	N.D

Table 3. Comparison of pump test hydraulic conductivity values to the model hydraulic conductivity inputs values for all aquifers.

Aquifer	In situ Hydraulic Conductivity (ft/day)	N	Model Hydraulic Conductivity (ft/day)	N
Coal	3.52	38	3.03 (calibration)	3897
			2.69 (1995 verification)	3897
Wasatch	.45	8	.2	3874
Clinker	51,000	2	31, 000	106

general head boundary module. MODFLOW calculates flow to and from constant head nodes and, if specified, will output these values to a binary file by front, right and lower face flow. Since the general head boundary assumes a constant head portion (clinker), as well as a semi-permeable zone (zone of alteration) and model domain (coal and Wasatch sediments) (Figure 2), it is possible to back-calculate values of conductance across the boundary:

$$C = \frac{Q_{(constant\ head)}}{Head_{(boundary)} - Head_{(model\ domain)}}, \qquad (1)$$

where the MODFLOW parameter conductance (C) is given as

$$C = T * \frac{cell\ width}{length\ of\ flowpath}. \qquad (2)$$

T is the harmonic mean of transmissivity between the clinker and the model domain and the length of flowpath is the path length between model domain and the clinker.

Given that T = Kb and combining the two equations, this becomes a restatement of Darcy's law

$$Q = K * \frac{H_2 - H_1}{L_2 - L_1} * (B * W) \qquad (3)$$

where K is the harmonic mean of hydraulic conductivity from data between the boundary and domain (zone of alteration), and (B*W) is the cross-sectional area of the model cell; head and flowpath as stated above. Both flowpath length and cell area are model calculated from user inputs in the model setup. The remaining parameter is the value of hydraulic conductivity in the boundary cell (zone of alteration). This can be derived using the following method: Given that the hydraulic conductivity in the model domain (Wasatch and coal) and the clinker is known from data, the geometric mean of hydraulic conductivity would be

$$K_{(geometric)} = (K_{(domain)} * K_{(clinker)})^{.5}. \qquad (4)$$

It is necessary to reduce this value to accommodate the width of the semi-permeable zone with respect to the model cell. Gerlach (1995) gives the width of the 'zone of alteration' as 250 ft. at North Rochelle. The value of boundary cell hydraulic conductivity becomes

$$K_{(boundary\ cell)} = \frac{250 ft.}{cell\ dimension} * K_{(geometric)}. \qquad (5)$$

For ease of computation, the zone of alteration was assumed to be 33% of the fully refined cell dimensions (825 by 948). This value actually ranges between 30.3% and 26.4%. However, this would assume that the altered zone traverses the minimum distance across a cell. The 33% is a reasonable and probably conservative value of the actual contact.

Recharge from Precipitation. The budget term for recharge from precipitation is also difficult because it requires quantifiable knowledge of precipitation/recharge relationships. Alternatively, we can assume that the amount is small, given the Powder River Basin water balance (Potential Evapo-transpiration >Precipitation), and investigate model sensitivity to the parameter.

Infiltration from summer convective storms and snowmelt is likely in the spring, especially on the more permeable surficial materials. There is little quantitative information on precipitation/infiltration dynamics in the Powder River Basin, however, assuming a range of precipitation over the basin of .833 - 1.33 ft/yr yields a daily value of .0029 ft/day using the geometric mean of the range (1.05 ft/yr). Further, assuming 1% falls on permeable material, and 2% of that infiltrates, a value of .6000E-06 ft/day may provide an initial approximation of vertical recharge from precipitation. This is equivalent to .00022 of total basin precipitation per year.

Anisotropy in the Coal. Cleat in coal aquifers are vertical fractures analogous to joints in sedimentary rocks (Henkle et al 1978). Cleat forms flowpaths in coal aquifers (Close and Mavor, 1991). The regularity of cleat orientation can cause groundwater flow to be anisotropic (Stoner, 1981). The Wyodak coal is considered to be an anisotropic flow medium (Martin et al, 1988, Belle Ayr PTMA).

La Point and Ganow (1986) reported two sets of cleat at Black Thunder. The more prominent set was oriented northeasterly. BLM (1992) states that the general belief in the Powder River Basin is that coal permeability may be "increased in the crests of anticlinal structures".

Dobson (1995) studied coal anisotropy in the Powder River Basin while working on an Abandoned Coal Mine Land Research Program (ACMLRP) grant. His findings suggest that near lineaments, maximum hydraulic conductivity in the coal is oriented along the major axis of the lineaments. His conclusions are based on three close- radius, multi-well pump tests conducted within the permit areas of three Powder River Basin mines. Dobson suggested a positive correlation between the orientation of K_{max} and the orientation of faults and lineaments in the Powder River Basin. One test was positioned to intentionally intercept the Corder Creek fault (Denson et al, 1980).

Two additional long duration, long radius pump tests wer conducted by the Bureau of Land Management west of Cordero mine in 1995. Analysis of these tests suggests that K_{max} may be orthogonal to Dobson's results. This suggests spatial variability of anisotropy, perhaps related to increased permeability along lineaments.

Storage coefficient. Storage coefficient data were obtained from the CPR database. The data is again spatially clumped near the coal cropline, with far fewer data than for hydraulic conductivity. There are 25 values of storage for the coal aquifer and 4 in the Wasatch aquifer.

The 25 data for the coal aquifer were minimally adequate to contour. Coal storage was contoured in the GIS using a spline contour algorithm. Coal storage declines downdip, ranging from .1 to 10^{-5}.

The four values of storage for the Wasatch aquifer were 0.1, located very near the cropline. This would indicate a single, unconfined value of storage throughout the study area. 0.01 was used in the model to reflect marginally confined conditions downdip.

Vcont. True three dimensional modeling would require complete data sets for the confining layer overlying the coal, including thickness and vertical hydraulic conductivity; this data intensity is not available for this layer. Quasi-three dimensional modeling assumes an aquifer relationship and does not explicitly specify all data for the confining layer. Vertical leakance is not explicitly modeled, there is no top surface, bottom surface, etc. Rather an implicit modeling method is used. Vertical leakance for both pre-and- post mine is input in MODFLOW using the following relationship for quasi-three dimensional models,

$$Vcont_{i,j,k+\frac{1}{2}} = \frac{1}{\frac{\frac{\Delta z_u}{2}}{K_{z_u}} + \frac{\Delta z_c}{K_{z_c}} + \frac{\frac{\Delta z_l}{2}}{K_{z_l}}}. \quad (6)$$

Where Δz_u is the thickness of the upper grid cell (i,j,k);
Δz_c is the thickness of the semi-confining unit;
Δz_l is the thickness of the lower grid cell (i,j,k+1);
Kz_u is the vertical hydraulic conductivity of the upper grid cell;
Kz_c is the vertical hydraulic conductivity of the semi confining layer;
and Kz_l is the vertical hydraulic conductivity of the lower grid cell.

Where vertical hydraulic conductivity is much smaller in the confining layer, the equation can be approximated as

$$Vcont = \frac{Kz_c}{\Delta z_c}. \quad (7)$$

For the present application, assuming a range of hydraulic conductivity for shale of 10^{-13} to 10^{-9} m/sec, $K_v \approx .1 * K_h$ (Freeze and Cherry, 1979), a ten foot thickness of the confining unit and converting units, Vcont is approximately 2.8E-09 to 2.8E-05 For the postmining scenario, the confining layer is absent, $K_{backfill} \approx K_{Wasatch} \approx .133$ to 1.33 ft/day; $K_v = K_h$ (isotropic) and absence of the confining unit, Vcont will range between $2.8 x 10^{-2}$ and $2.8 x 10^{-3}$ ft/day-ft assuming a 50 ft thickness between node centers. The simplified equation (7) for Vcont is still appropriate. A value of $2.0 x 10^{-2}$ ft/day-ft was used in the model with sensitivity.

Sources and Sinks

Water sources and sinks for the model scenario include the following. Aerial recharge (distributed source), mine pits modeled as drains (point sink) and coal bed methane production (point sink).

Wells. Stress rates for CBM were calculated by assuming initial pump rate of 4813 ft/day (25 gal/min), from Wyoming State Engineer's Permits, and decaying that pump rate through time assuming the following relationship.

$$Q_{current} = Q_{initial} * Stress \quad period^{.2} \qquad (8)$$

All pump rates are then calculated for an anticipated life of well production of ten years.

Surface Mining. Stress rates for the mine pits are presented in figure 3 and are based on the Theis non-equilibrium well equation, adapted to accommodate 'big wells'.

$$Q_{pit\ inflow} = \frac{Ts}{114.6} * W(u) \qquad (9)$$

where

Q is pit inflow in gal/min;
T is aquifer transmissivity in gal/day-ft;
W(u) is 'well function of u' representing the exponential integral;
s is aquifer drawdown in feet measured at the pit face, here assumed to be 60% of the saturated thickness, t is the time the 'well' is discharging, here taken as 365.25 days and 'u' is

$$u = \frac{1.87 * r^2 * S}{T\ t} \qquad (10)$$

where S is dimensionless storage coefficient and r is the distance in feet from node center to pit face calculated as

$$r = \frac{2}{\pi} * (L * W)^{.5} \qquad (11)$$

where L and W are the cell length and width, here equal to 825 ft and 948 ft, respectively.

Knowing Q, it is possible to directly calculate MODFLOW conductance from the relationship

$$Conductance = \frac{Q}{Head_{cell} - Head_{out\ of\ cell}} \qquad (12)$$

where conductance is as previously stated, and is the needed parameter in the MODFLOW Drain package; $head_{(in\ cell)}$ is taken as the elevation of the drain, and $head_{(out\ of\ cell)}$ is here equal to the steady-state head.

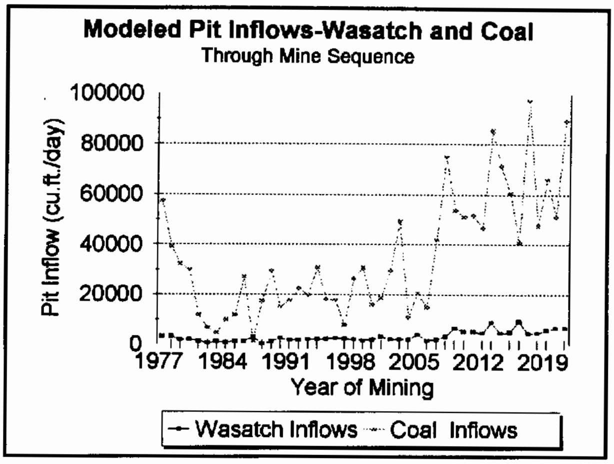

Figure 3. Cumulative modeled pit inflows for Jacobs Rance, North Rochelle and Black Thunder mines, through presently anticipated end-of-mining.

Numerical Parameters

The strongly-implicit procedure (SIP), slice successive over-relaxation (SSOR) and Pre-conditioned Conjugate Gradient (PCG2) solvers were all tested on the model (McDonald and Harbaugh, 1988; Hill, 1990). Best success was achieved with the PCG2 solver.

The PCG2 solver uses Picard iterations to solve the system of equations (Hill, 1990). The polynomial preconditioning option was used in this model. HCLOSE and RCLOSE, the head change and residual change criteria, and a matrix scaling alternative are other user supplied inputs. Budget error for all model runs was less than .05% for an individual stress period, with cumulative error less than .01%

Calibration

Selection of Calibration Targets and Goals

Coal. Calibration targets for the coal can be described as all wells that possessed groundwater elevation data representing premine conditions. Initially these were conceptualized as 1975 and before. Assuming that negligible impact occurred in the model domain before 1977, the number of wells was significantly increased. Targets at North Rochelle were initially excluded from the calibration due to the relatively late time data (approximately 1980). The need for an assessment of initial conditions of North Rochelle necessitated the inclusion of this data in the model calibration phase. The coal aquifer was also calibrated to time series data *outside* of the refined grid that was representative of premine groundwater elevations at Coal Creek, Rochelle, Keeline and North Antelope mines. This data was only used for initial calibration, assuming that the earliest time data represented 'baseline' conditions and that water levels had been essentially unimpacted. A single additional BLM coal monitor well was used in an attempt to add data west of the mines where the coal potentiometric surface was not monitored. This data is from 1995 and assumes no significant impact at this point from 1975 to 1995.

Wasatch. Initially a similar series of wells to the coal series was selected and expanded the targets to 1977 and before. Problems arose in the north due to the mapped 'full seam' Wyodak coal line lying to the west of specified Wasatch wells at Coal Creek mine. One possible explanation for this is that wells designated as Wasatch wells at Coal Creek actually are completed in quaternary deposits. This issue may be resolved when the Coal Creek area is modeled. For the present model, Wasatch targets were limited to the refined grid area. This limited the Wasatch validation targets available, but is reasonable because of the lenticular nature of the Wasatch formation.

Goals. Calibration for the model was evaluated with respect to three quantitative goals. Mean error was checked as an estimator of model bias. Absolute error, or the maximum error observed at a single calibration location was minimized as a secondary criteria to Root-Mean-Square error. Root- Mean-Square error given as

$$RMS = \sqrt{\sum_{i=1}^{n} \frac{(observed - predicted)^2}{n}} \qquad (13)$$

was used as the primary model goal.

Quantitative Analysis

Calibration to observed groundwater elevations was done by iteratively adjusting hydraulic conductivity in the Coal aquifer, within the constraints of the conceptual model and observed hydraulic data. This was not done in the Wasatch due to the scarcity of data and an observed issue with Wasatch well completion intervals between Jacobs Ranch and Black Thunder. Data from 7 mines and one expired lease (Keeline) for the coal aquifer was included. Table 4 summarizes the results of calibration and verification.

Calibration for the Wasatch formation was limited to data from Jacobs Ranch (JRM) and Black Thunder. Groundwater elevations observed at targets outside of the refined grid area were deemed unlikely to represent water bearing units present within the refined grid area. Calibration targets for the Wasatch were fewer than for the coal. Completion intervals for the Wasatch target wells were examined to address completion in the same water bearing unit, and were found to vary. Wasatch calibration error was compounded by this completion inconsistency.

Discussion. Coal calibration exhibits minimal RMS error and minimal bias. The maximum absolute error of 8.5 ft occurs at well NA10A, a North Antelope well considerably south of the refined grid area. When RMS error dropped below 10 ft, water level changes became more difficult to achieve at individual targets. Significant reduction in hydraulic conductivity in the coal at both North Rochelle and Jacobs Ranch was necessary to duplicate the steep hydraulic gradients.

An improved calibration using both Jacobs Ranch and Black Thunder overburden targets is unlikely given the variability in completion methods between mines for the overburden targets. The Wasatch RMS error considering only JRM wells may be improved with deterministic manipulation, although hydraulic data and the aforementioned completion inconsistencies in the Wasatch does not seem to justify this method.

JRM targets calibrate better than Black Thunder mine because the model delineates Wasatch water bearing units the way the Jacobs Ranch wells are completed; as a single, marginally confined aquifer of thickness equal to SURFACE ELEVATION - TOP OF COAL. This is not an accurate interpretation of Wasatch lenses, but the additional data needs to delineate individual water bearing units in the Wasatch are significant.

Improved calibration for the Wasatch can be qualitatively discussed. Iteratively altering hydraulic conductivity at certain model locations could improve the RMS error for the layer. Altering global vertical recharge (precipitation) may positively affect RMS error, and could be used to improve calibration for the combined Wasatch data sets, but any comparison would be flawed by the different completion interval of the targets.

Sensitivity Analysis

Certain model parameters can be investigated by varying the parameter value, and comparing model

Table 4. Results of RMS, mean and maximum absolute error for Wasatch and coal aquifer targets for 1975 (premining), 1985, and 1995. N.D. indicates that insufficient targets were available to verify the application.

RUN	Coal Model Error (ft)			Wasatch Model Error (ft)		
	RMS	Absolute (row,col)	Mean	RMS	Absolute (cell)	Mean
Calibration	3.78	8.5 (71,78)	0.49	10.1	20.5 (17,40)	1.38
Verif 1985	9.6	24.6 (43,39)	-4.32	23.8	37.1 (27, 27)	15.39
Verif 1995	6.42	14.4 (48,27)	0.54	N.D.	N.D	N.D

response to the variability at targets. This provides insight into the sensitivity of the model to the parameter value.

Anisotropy in the coal. Best model prediction of coal target groundwater elevations occur when column hydraulic conductivity is a factor of two times row hydraulic conductivity at node centers. This suggests that for the study area, the coal is moderately anisotropic; and K_{max} is oriented northeast-southwest, or approximately along model columns. Targets are steady state targets. Table 5 summarizes the results.

Boundary. Model RMS error was checked for sensitivity to Coal and Wasatch boundary conditions. Results are presented in table 6. RMS error for groundwater elevations for both the Wasatch and Coal were compared using a constant head and general head boundary. Results indicate that the model is not sensitive to the changing boundary conditions under steady state conditions. Model bias is slightly improved with the general head boundary. This suggests that the general head boundary approximates the constant head boundary for steady state conditions, the expected result.

Wasatch Formation Hydraulic Conductivity Sensitivity. Table 7 presents the results of sensitivity analysis on the hydraulic conductivity of the Wasatch Formation sediments. The targets are Jacobs Ranch targets only. The model is not especially sensitive to change in Wasatch hydraulic conductivity. RMS error increases as hydraulic conductivity increases for values over .2ft/day. Maximum absolute error is inversely related to hydraulic conductivity for all values of K. Mean error varies within a small positive range for all values greater than .2 ft/day. The mean error indicates that the model narrowly underpredicts the initial observed static water levels when global hydraulic conductivity in the Wasatch is .2 ft/day or greater and overpredicts for hydraulic conductivity less than .2 ft/day. The number of dry cells increases with each of the model runs as hydraulic conductivity increases.

Model Verification

The years 1985 and 1995 were selected as dates to verify the model application. These dates represent the approximate onset of increased mining activity in the basin (1985) and the onset of the proposed Coal Bed Methane production (1995). Similar to calibration, verification targets were selected in the coal and Wasatch aquifers and modeled water levels were compared to observed data. Where necessary, individual values of hydraulic conductivity were adjusted to improve the verification, since the location of verification targets differed from calibration targets. The nature of the mining process involves the destruction of targets: there are fewer verification targets than there are calibration targets (1975>1985>1995). Results of error analysis is presented in table 4.

All available database targets at the time of modeling were considered in the verification process. Individual targets were excluded for multiple completion, and location on the eastern boundary only.

Verification Discussion

1985. RMS error increased in the 1985 verification in the coal, as did mean error. Several possible reasons for this are suggested below.

- Wells at North Rochelle were used during calibration even though they were not described as 'premining' wells in the conceptual model. The time of first observation was 1980-1981 for these wells. These wells were added to improve the 1985 verification in the south of the study area. The extent that these values reflect premine groundwater elevations will effect model accuracy.

Table 5. Results of sensitivity analysis of anisotropy in the coal aquifer.

Column to Row Anisotropy	Coal Model Error (ft)		
	RMS	Absolute (row,col)	Mean
3:1	4.83	12.30 (11,10)	1.75
2:1	3.92	8.40 (71,78)	0.74
1:1	6	18.54 (7,8)	-0.62
1:2	8.43	28.66 (54,61)	-1.66

Table 6. Results of sensitivity analysis for constant head vs general head boundary condition on C_3, W_3, (Figure 1)

Boundary	Coal Model Error (ft)			Wasatch Model Error (ft)		
	RMS	Absolute (row,col)	Mean	RMS	Absolute (row,col)	Mean
General Head	3.78	8.5 (71,78)	0.74	10.1	20.50 (17,40)	1.38
Constant hd	3.68	8.6 (71,78)	1.07	10.09	20.51 (17,40)	1.49

Table 7. Sensitivity analysis of global Wasatch Formation K. Hydraulic conductivity of the first model layer was allowed to vary, excluding only the general head boundary cells.

Global Wasatch Formation K	Wasatch Formation Model Error (Steady State Targets) (ft)		
	RMS error	Maximum Absolute (cell)	Mean error
.04 ft/day	15.42	28.15 (37,31)	- 2.715
.2 ft/day	10.1	20.5 (17,40)	1.38
1.0 ft/day	10.44	20.03 (17,40)	1.82
2.0 ft/day	11.99	19.55 (17, 40)	1.45
3.5 ft/day	13.17	19.08 (17,40)	1.11

- A preponderance of 'near pit' wells and the compounding of this with pit (stress) location inaccuracies stated below is a probable error source.

- The pit inflows are calculated from an assumed 60 percent drawdown at the pit face. This is an approximation and may not be appropriate for every stress period.

- Paper PTMA maps were automated to GIS and computer matched to the MODFLOW grid to determine the historic mining sequence. Date of mining for Black Thunder on the paper maps was specified as pre-1992 only for the period from 1977-1992. Exact date of historic mining could not be determined.

Two methods were devised to assign yearly stress periods to historic mining. Lacking additional information, it was assumed that mining proceeded uniformly through the period. A location(s) of the initial box cut was selected and mining moved in a single direction through the historic mined areas, thus distributing the disturbance systematically and uniformly through the years in question. This was the method employed at Black Thunder.

The extent of the historic mining was assumed to be one year prior to the reclamation activity for a particular area at Jacobs Ranch. For example, if reclamation was mapped as occurring in 1978, it was assumed that mining occurred in 1977.

Where cells were located on the coal/clinker/Wasatch boundary and the cell was indicated as a mined node, the node was not simulated as mined. This is a result of the assumptions of the Cauchy boundary which state that no change in storage is allowed in the semi-permeable zone.

Finally, modeled output is specified at node centers. This is a result of the finite difference method. Refined cells (825 x 948) have data reported at node centers and may have targets located up to 628 ft distant from the node center and still be within the cell.

1995. In general, mining is progressing downdip (westward), away from the cropline, and fewer coal/clinker/Wasatch boundary cells are encountered. This results in a more complete areal delineation of surface mining stress. The mining sequence that forms the surface mine stress locations for the period 1985-1995 is much less subjective.

The increased RMS error that is observed in the 1995 verification (when compared to calibration RMS error) may be caused by some or all of the previously mentioned (1985) factors. 1995 model mean error indicates that the observed underprediction of drawdown is no longer present. The model for 1995 is essentially unbiased. Further, RMS error at coal targets has declined by 33% from 1985 to 1995.

Maximum absolute error in the model domain moves from a south, unrefined cell to the Black Thunder permit area for 1985 and 1995. This may be directly attributable to the number of near-pit wells included in the coal targets.

Discussion. Verification of the coal targets improves with time as mining moves away from the cropline, the surface mine pit locations are better documented, and the number of mined cells increase. Several complications that are unresolvable in the model process are the lack of continuity of model targets through time due to the destruction of wells (targets) as the pit advances, the extent to which simulated inflows approximate actual pit inflows, and the disproportionate number of near pit wells.

Water Budget and Mass Balance

The modeling process produces intermediate output in 1985, 1995, and 2021 with and without coal bed methane production. Table 8 summarizes the mass balance. Model recharge from clinker increases as stresses increase. Boundary inflows are conceptually unbounded, so unrealistic inflows can develop. Modeled steady state recharge shows recharge ranges from 540 - 750 gal/min. Average transient state recharges range from 730 gal/min from 1977-1985 to 2400 gal/min in the 1996 - 2021 model period. The mapped surficial clinker in the study area is 66 square miles. Assuming uniform permeability, and no other outflows from the clinker, it would require about .1 ft of water over the clinker area to maintain dynamic equilibrium. Judging from this, the recharge values seem plausible. Net declines in water exiting the model domain through the south and west constant head boundary can be expected through the active stress periods. Summing cumulative totals will give net change in stored water within the study area plus the cumulative model error.

Predictive Simulations

The selected measure of model accuracy is to compare model predicted groundwater elevations to observed groundwater elevations in the coal and Wasatch aquifers. Based on this comparison, RMS error of the observed vs predicted results give a quantifiable estimate of model accuracy.

Extent of Predicted Drawdowns

Mining. The five foot drawdown contour in the coal is approximately five miles west of the mine permit boundaries as of 1995. By 2021, the five foot drawdown contour from surface mining only is approximately three miles west of highway 59 and approaches the south model boundary (Figure 4).

The five-foot drawdown contour in the Wasatch formation is essentially contained within the permit boundaries through 2021 (Figure 5)

Mining + CBM. The effect of coal bed methane is seen

Table 8. Cumulative mass balance and global model water budget through 2021. The 1996 - 2021 time period is modeled with and without coal bed methane production.

Date	CBM Wells (ft^3)	Pit Inflows (ft^3)	Precip Recharge (ft^3)	Net Recharge (+) / Dischage (ft^3); Boundary	Net Constant head Recharge (+) / Discharge (-) (ft^3)
1977-1985	-0-	105790000	22571000	460500000	-395930000
1986-1995	-0-	1906700000	25036000	2119500000	-386150000
1996-2021	-0-	3813700000	64459000	4345000000	-863440000
1996-2021	402690000	3792000000	64459000	4385000000	-540030000
Cumulative	402690000	.58045E+10 - .58262E+10	112070000	.69250E+10 - .69650E+10	-.13221E+10 - -.16455E+10

in the 2005 scenario (Figure 6). Coal bed methane increases the western extent of the five-foot drawdown contour to the western model boundary and to the south to the southern boundary. The contour affects (> 5 ft of drawdown) the south boundary at five cells. Coal drawdowns recover significantly following the cessation of pumping in the modeled scenario (Figures 4 and 6).

Summary, Conclusions and Implications of Modeling

This report documents the methods used to deterministically model groundwater stresses related to energy impacts in the Wyodak Coal and Wasatch aquifer and provides a method for future cumulative impact assessment. Some general conclusions that are a result of this study follow.

General Conclusions.

- The distribution of groundwater sampling needs to be addressed. Groundwater elevation and hydraulic data is clumped near the cropline; little additional information may be statistically required to adequately define the potentiometric surfaces in these areas. Future sampling to the west of the mine permit areas is recommended to determine the adequacy of cumulative predictions and to assess the need for update of this document.

- Geologic data on the lenticular Wasatch sand aquifers needs to be developed if impacts to this formation are to be accurately modeled.

- A conscientious effort to assess data needs by regulators and permitees will improve the science and reduce monitoring costs.

- Aquifer testing in the backfill and clinker has not been done to the extent necessary to evaluate backfill hydraulics. This should be a priority.

Implications of Modeling

Data collection prior to this modeling effort was intensive. Data update was sought for the study area through cooperation of the area mines, the Bureau of Land Management and the other agencies involved in the cooperative agreement. The model is site specific to the study area, and although regional in scope, groundwater impacts are best approximated for the three subject mines within the refined grid (Black Thunder, North Rochelle and Jacobs Ranch) (Figure 1). Data needs for regional modeling of this nature are extensive. Decisions must be made on data quality, distribution and utilization that are best addressed using a GIS. This will be costly, but will improve the science and increase the acceptance of the work.

Coal bed methane is regulated separtely from surface mining. Coal bed methane development increases the extent of drawdowns in the aquifers modeled. It will be necessary to assess the relative

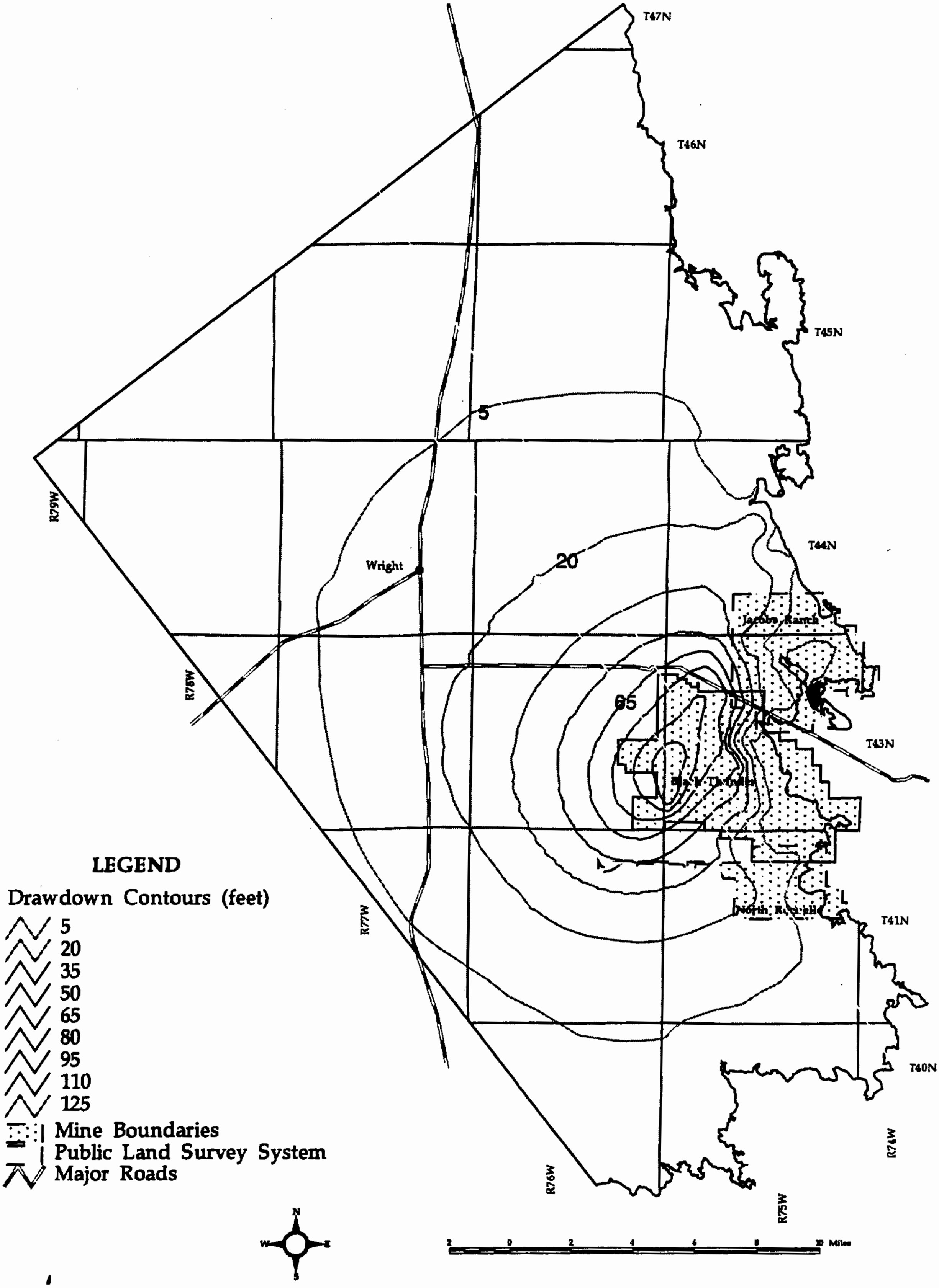

Figure 4. Simulated drawdowns in the coal after gas and mining development (Year 2021).

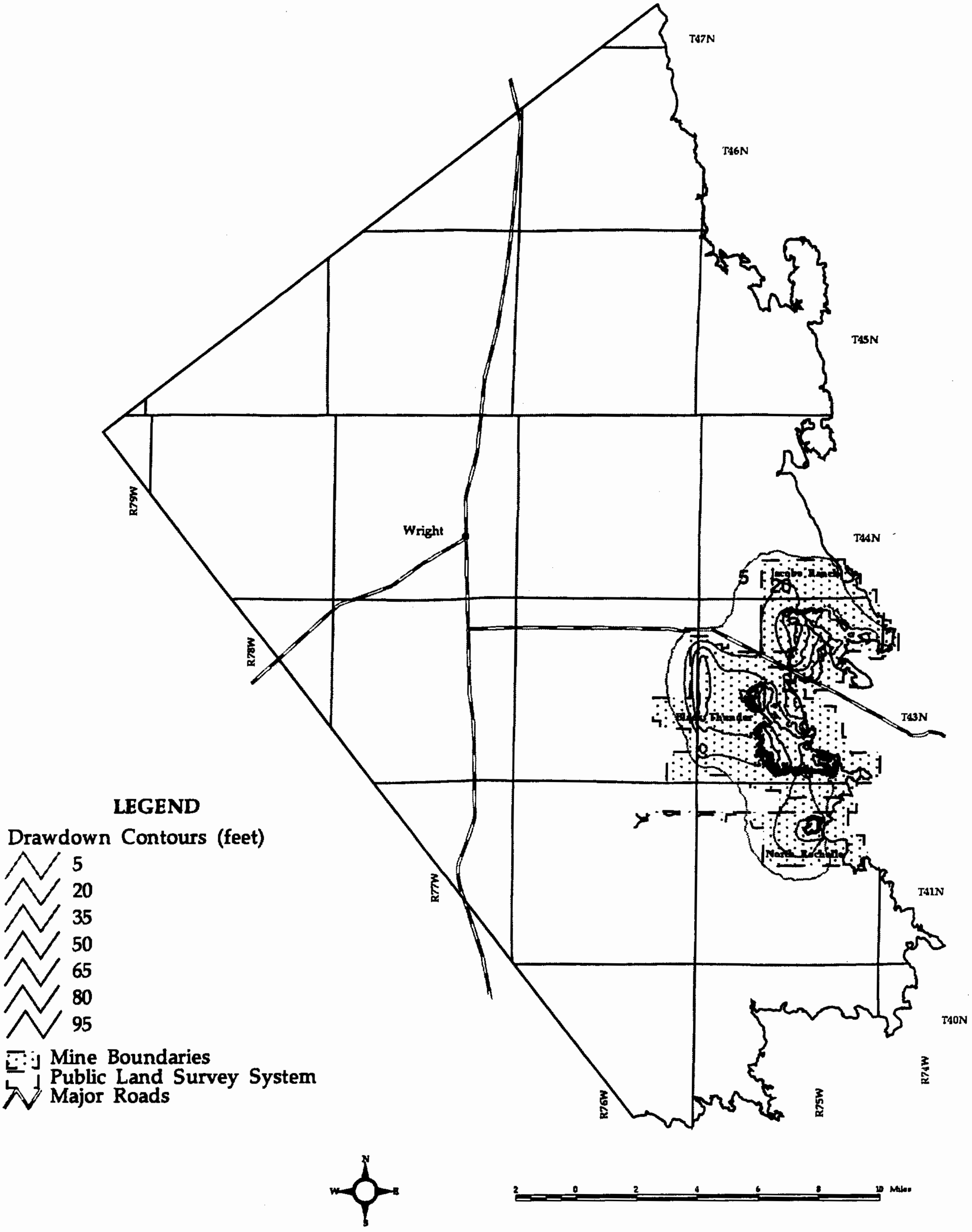

Figure 5. Simulated drawdowns in the Wasatch aquifer after gas and mining development (Year 2021).

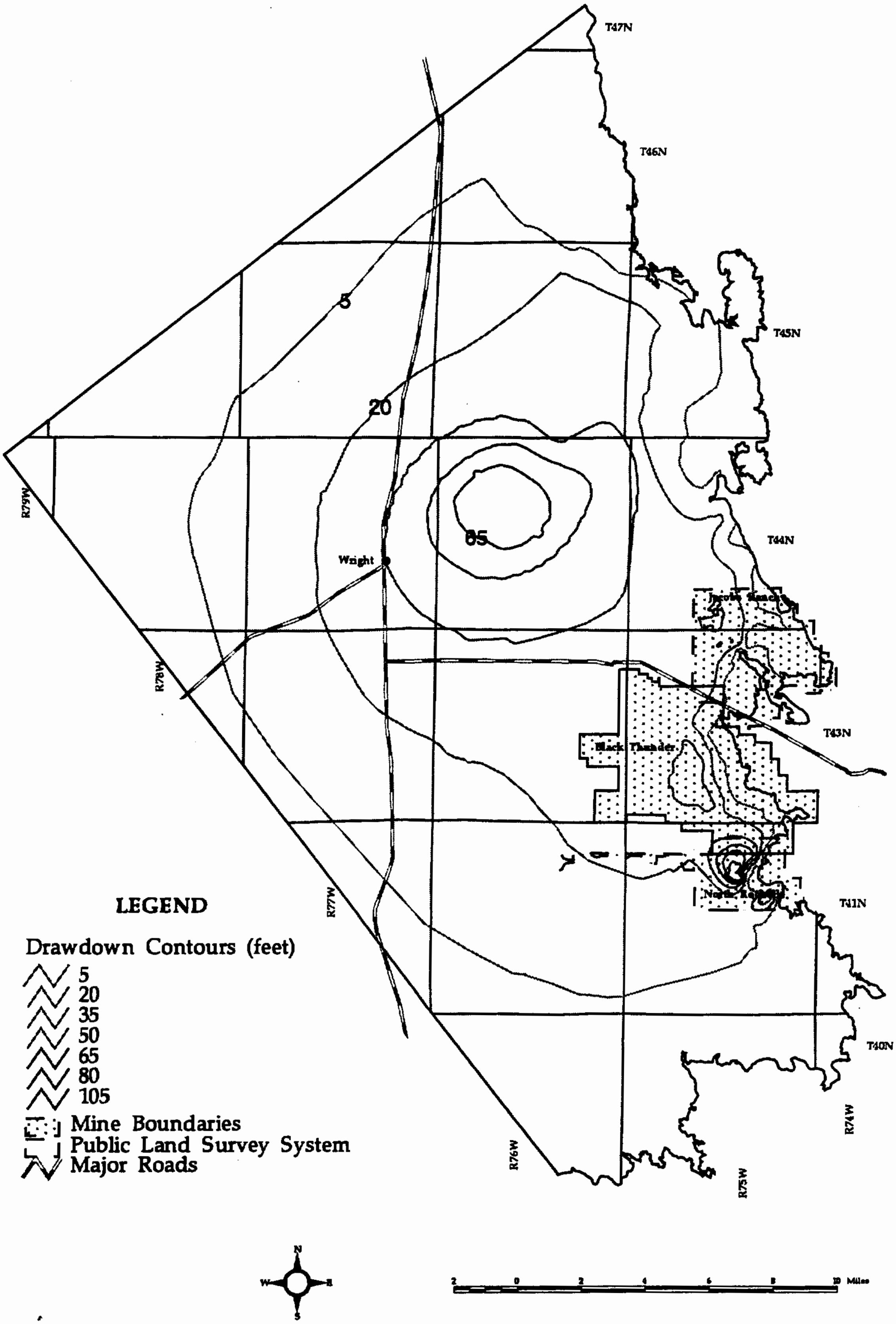

Figure 6. Simulated drawdowns in the Coal after gas development (Year 2005).

porportion of drawdowns attributable to each industry if liability for impacted wells is questioned. Modeling of this natures addresses these concerns and provides a useful tool for all parties.

To the authors knowledge, the methods utilized to assess Coal/Clinker/Wasatch boundary recharge presented in this report are the first attempt to quantify this flux using other than determininstic methods. While the results are reasonable, they can be improved and verified with testing. Stable isotope assessments using tritium and radioactive carbon provide quantification of recharge by non-Darcian methods.

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