8.0 CABALLO CREEK SUB-AREA MODEL

The Caballo Creek sub-area model was constructed to aid in establishing criteria for the regional model and to evaluate the potential impacts of CBM development that are more reasonably assessed at a smaller scale than the regional model. As with the regional model, the VMODFLOW program (v.3.0) was used to complete pre-processing, modeling, and post-processing, including zone water budgets.

The Caballo Creek area has been extensively developed for coal and coalbed methane and has a long history of groundwater monitoring that extends back to the late 1970s. Mining started in 1974 at the Belle Ayr mine and was followed closely by the Caballo, Cordero, and Rojo Caballo mines in the late 1970s and early 1980s. The Cordero and Rojo Caballo mining operations have since been merged. CBM operations have been active in this area since about 1992, when the Marquiss field was initially developed by Martens and Peck. Groundwater level data have been collected in the vicinity of these CBM operations at several nested BLM monitoring wells since early 1993. Earlier groundwater monitoring data are available from the Belle Ayr, Caballo, and Cordero mines. As a result, the Caballo Creek area provides a unique opportunity to model the influences of nearly complete CBM development where sufficient monitoring well data provide good calibration points.

8.1 Model Grid and Layering

The area of the Caballo Creek sub-area model is shown in Figure 8-1. Table 8-1 summarizes the model setup and assumptions. The model grid (Figure 8-1) consists of 62 cells in the north-south direction (rows) and 108 cells in the east-west direction (columns), for a total of 6,696 cells per layer. The grid spacing is uniform throughout the model and is one-quarter mile (about 400 meters) in both the north-south and east-west directions. The uniform grid spacing allows for easier manipulation of the model in ArcView, Surfer, and Access, while maintaining the integrity of the model. The model grid was set up in the NAD27 UTM Zone 13 meters coordinate system.

The model was constructed with 11 layers, as summarized in Table 8-2. Model layers 1 through 6 represent the Wasatch Formation, and layers 7 through 11 represent the upper part of the Fort Union Formation. A typical cross-section through the model is shown in Figure 8-2.

The top of the uppermost layer (layer 1) is the topographic surface. This surface was constructed from downloaded 1:250,000 USGS DEMs for the Caballo Creek area. The x,y,z data from the DEMs were extracted into a .dat file using Surfer software. The extracted .dat files were combined, and the coordinates were converted from Lat/Long to the NAD27 UTM Zone 13 meters coordinate system using Tralaine software. Surfer was used to grid this file at one-quarter mile spacing using the "Natural Neighbor" algorithm. The grid file was then imported into VMODFLOW as the surface of layer 1 (Figure 8-2).

The uppermost layer (layer 1) represents the surface geologic units that include shallow Wasatch geologic units (claystone, siltstone and sandstone) and unconsolidated alluvial sands within creek valleys. This layer was assigned a uniform thickness of 30 feet (10 meters). The hydrologic properties within this layer were varied to reflect the different characteristics of the geologic units within this layer (Table 8-1).

Table 8-1
Summary of Caballo Creek Model Setup and Assumptions

Project	Powder River Basin (PRB) Oil& Gas Environmental Impact Statement (EIS) - Powder River Basin Groundwater Impacts
Area	Caballo Creek Drainage Basin, Powder River Basin in northeast Wyoming
Code	MODFLOW-96. Pre- and post-processor: VMODFLOW v.3.0
Time modeled	Steady State: 1975 (Pre-mining); Transient State: 1975 to 2200
Dimensions	X = 43.2 Km, Y = 24.8 Km (10,713.6 Km^2, 4,131.3 sq. miles)
X coords	437,711 – 480,911 meters
Y coords	4,871,087 – 4,895,887 meters
Coordinates	North American Datum (NAD)27 Universal Transverse Mercator (UTM) Zone 13, meters
Rows, columns	No. of rows: 62 No. of columns: 108 (6,696 cells/layer)
Grid spacing	400 meters x 400 meters (¼ mile x ¼ mile) for the entire model
Layers/type	No. of layers: 11. Layer 1: Unconfined: Layers 2-11 Variable T, S
Surfaces	**Coal surfaces and isopachs:** Goolsby, Finley, and Associates: 2001 **Steady-state potentiometric surface:** Modified after Daddow 1986, BLM Well Data, RAG Belle Ayr Mine Monitoring well data **Surface topography:** U.S. Geological Survey (USGS) Digital Elevation Models
Geology	**Coal Units:** Goolsby, Finley, and Associates (2001) **Surface Geology:** USGS: "National Coal Resource Assessment, 1999 Resource Assessment of Selected Tertiary Coal Beds and Zones in the Northern Rocky Mountains and Great Plains Region" (USGS 1999a)
No-flow Boundaries	Each layer has a different no-flow boundary area that is determined by the formation the layer represents.
Drains	Regional groundwater flow to discharge areas beyond the model boundaries, such as the Powder River, was simulated using drain nodes in layers 7 through 11 at the northwestern "no-flow" boundary.
Recharge	Basin-wide infiltration: 0.025 inches per year Clinker infiltration: 0.21 inches per year
Rivers (constant head)	**Intermittent Rivers**: The lower part of Caballo Creek was set as drain nodes with the surface elevation minus 3m as the drain node elevation.
Coal Mines and CBM Wells	**Mine plans and locations**: Wyoming Department of Environmental Quality (WDEQ) and Office of Surface Mining (OSM) annual reports from mining companies; Gillette Area Groundwater Monitoring Organization (GAGMO) 15-year report. **CBM Wells:** Input as drain nodes. Existing CBM wells taken from the Wyoming Oil and Gas Conservation Commission (WOGCC) database dated 7/20/01. Projected coal bed methane (CBM) wells were developed by the Bureau of Land Management (BLM), WOGCC, Greystone, and Applied Hydrology Associates (AHA) with input from CBM industry representatives.
Solver	Steady-state: WHS (Waterloo hydrologic solver); Transient-state: WHS.

Table 8-2
Caballo Creek Model Layers

Model Layer	Geologic Formation/Member	Geologic Unit	Predominant Lithologies
1	Wasatch Formation	Upper Wasatch Formation and Alluvium	Sandstone, siltstone, claystone
2, 3		Shallow Wasatch Unit	Sandstone, siltstone, claystone
4		Intermediate Wasatch Unit	Sandstone, siltstone, claystone
5		Deep Wasatch Unit	Sandstone, siltstone, claystone
6		Confining unit at base of Wasatch Formation	Siltstone, claystone
7	Fort Union Formation	Upper Fort Union Coal (Unit 1)	Coal (minor sandstone, siltstone)
8		Confining unit between coal units	Siltstone, claystone
9		Upper Fort Union Coal (Unit 2)	Coal (minor sandstone, siltstone)
10		Confining unit at base of coal units	Siltstone, claystone
11		Lower Fort Union sand aquifer units	Sandstone, siltstone

Layers 2 through 5 represent zones of the Wasatch Formation where discontinuous sandstone units occur. The discontinuous nature of the sandstone units is difficult to accurately simulate. However, this simulation was attempted by assigning hydrologic parameters to these layers that represent mixed sandstones and siltstone/claystone.

The lowermost layer (layer 6) within the Wasatch Formation represents claystones that act as a confining unit between the underlying coal zone of the Fort Union Formation and the discontinuous sandstones within the Wasatch Formation. This layer was set at a uniform thickness of 30 feet (10 meters) above the top of the upper Fort Union Formation coal zone. The vertical permeability of this layer in any location reflects its ability to act as a confining unit between the Fort Union coal zone and the overlying deep Wasatch sandstones. The assigned thickness of this unit influences the rate of leakage from the discontinuous sandstone unit layers (primarily layer 5). However, varying the vertical permeability assigned to the layer in any area can effectively be used to compensate for variations in thickness since the leakage is proportional to the product of the thickness and the vertical hydraulic conductivity.

Layers 7 through 11 represent the upper part of the Fort Union Formation. The top and bottom surfaces of the two coal-bearing hydrogeologic units of the upper Fort Union Formation that occur in this area, represented by layers 7 and 9, were created from unpublished data compiled and consolidated by Goolsby, Finley and Associates for the modeling effort. As the coal-bearing units split and merge, the hydraulic properties assigned to the layers representing coal-bearing units and intervening units change accordingly. The coal-bearing units transition into more highly permeable clinker in outcrop areas.

The east-west cross-section in Figure 8-2 shows the model layer setup and the variability in the thickness of model layers. The different colors within individual layers indicate specific hydraulic conductivities assigned and no-flow zones that are described in subsequent sections.

Figure 8-1 Caballo Creek Model Area and Grid

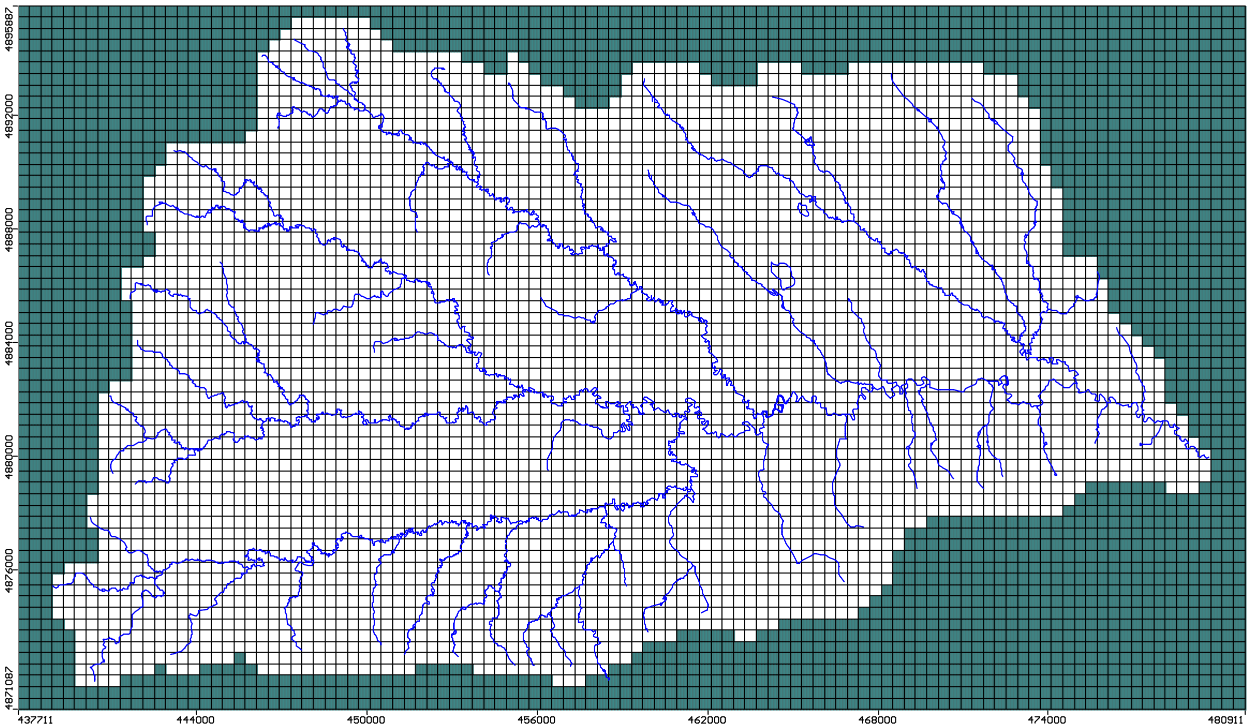
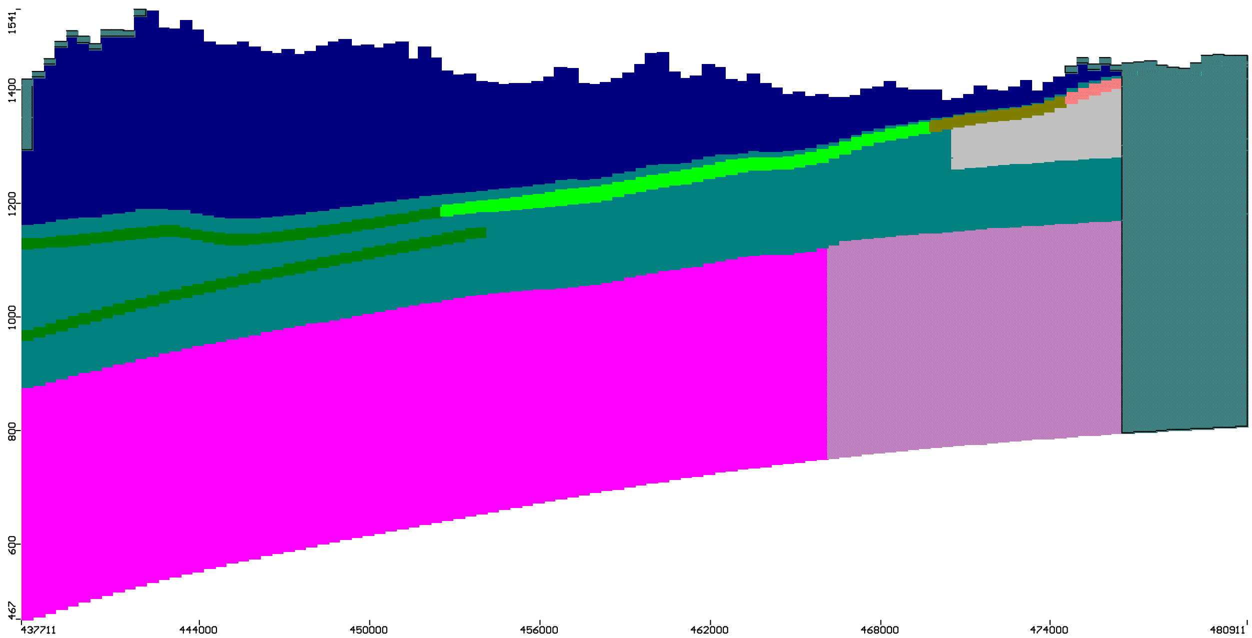


Figure 8-2
Caballo Creek Model - Typical East-West Cross-Section



8.2 Boundary Conditions

Boundary conditions used in the Caballo Creek model include no-flow and drains (rivers, mines, CBM wells, and model outflow).

No-flow cells were assigned to the model grid that was outside the area of the outcrop for the geologic units represented by each model layer. The extent of no-flow cells varies for each layer. Use of no-flow cells helps mitigate the effects of layer displacement caused by minimum thickness. The no-flow cell configuration was identical for some layers, but in general, fewer no-flow cells surrounded the active area with increasing depth of the layer. Recharge was applied to the highest active cell so, in effect, the highest active cell acts as if it were at ground surface. The extent of no-flow cells is shown in Figure 8-1.

No-flow cells were also designated in river areas where the river elevation was below the base of any given layer. Some of the fingers along the coal outcrop were also set as no-flow because they contribute little to the regional flow system but can cause considerable difficulty when attempting to achieve convergence of the model.

Interaction between rivers and adjacent shallow aquifers is simulated in the model by drain nodes along the lower portion of Caballo Creek. The head set in the drain nodes was based on the topographic elevation of the river at each node location.

Active surface coal mining is simulated in the model by setting drain nodes in the coal layer at appropriate locations. Groundwater will enter an active drain node from an adjacent node as long as the potentiometric level in the adjacent node is higher than the elevation of the drain.The rate of drainage decreases as the potentiometric elevation in the adjacent node is lowered by drainage. Drain nodes can be made inactive by setting the drain elevation much higher than the potentiometric elevation of the adjacent node. Unlike constant head nodes or general head nodes, drain nodes will not add water to adjacent nodes in this condition. The use of drain nodes to simulate surface mining allows the water levels to recover when active mined areas are backfilled and reclaimed.

The mining sequence was simulated from reasonably foreseeable mine plans for geographic locations projected to be mined as incremental impacts in 1-year stress periods from approximately 1975 (the earliest mining along the PRB outcrop in this area) to 2021. Each drain node is activated only during the period of active mining in the area represented by the node, typically set at 3 years. After this period, the drain node is made inactive, which simulates backfilling and reclamation of a pit area after active mining ends. The location and timing of drain nodes simulate past and future mining based on historical mining records and life of mine plan maps included in mining permit applications and 5-year mining plan updates. The water level in a drain node in an active mine area is set a few feet above the bottom elevation of the coal layer.Each drain node is input individually because the elevation of the coal bottom varies.

Drain nodes were also set along the western and northern boundaries of the model to allow regional groundwater flow to continue to the northwest if prevailing head gradients indicate that this flow would occur. Drain elevations were set based on steady-state, pre-development calibration data.

8.3 Recharge

The Caballo Creek area receives between 10 and 12 inches of precipitation per year (USDC/NOAA, 1979). The Caballo Creek drainage is naturally ephemeral. Groundwater aquifers recharge from infiltration of direct precipitation (rain and snowmelt), runoff in creek valleys, and standing water in playas, reservoirs, and stock ponds.

Precipitation provides a minimal source of recharge over most of the area because the climate and surface features restrict significant infiltration. Only a small percentage of the available precipitation infiltrates, while the majority runs off. Area-wide recharge, which includes recharge in creek valleys and ponds, expressed over the entire area, is expected to be less than 1 percent of the total precipitation, on average. This rate would be equivalent to less than 0.12 inches per year. Steady-state calibration indicated that this amount of area-wide recharge appears to be realistic. A value of 0.025 inches per year was indicated by the steady-state calibration. This value is similar to the recharge rate of 0.03 inches per year established from steady-state calibration of the regional model.

Infiltration is significant where surface geologic units are more permeable, such as in alluvial valleys and clinker that occur along the eastern outcrop area of the upper Fort Union coal zone. The clinker areas are generally considered to form recharge areas for the coal. However, although the clinker provides good potential for infiltration, the rate of recharge to the coal may be limited by the presence of a low-permeability zone at the contact between the clinker and the underlying coal or shale. Thick, clay-rich soils over flatter surfaces also may retain the downward movement of water (Heffern and Coates 1999).

Pre-mining potentiometric data and interpretations from many of the permit applications for coal mines tend to support the potential for clinker recharge to the coal, but the rate of recharge is relatively low. Recharge in the clinker areas is expected to be between 2 and 5 percent of the total precipitation, or equivalent to between 0.2 to 0.5 inches per year. Steady-state calibration indicated that this amount of recharge in the clinker areas appears to be realistic. A value of 0.21 inches per year was indicated by the steady-state calibration.

8.4 CBM Wells

The model simulates active CBM wells by setting pumping wells in the appropriate coal layer at the well locations. The location and reported pumping rates of existing CBM wells over time were downloaded from the WOGCC database and were imported into the model. Future CBM operations are based on an assumed well life of 7 years.

8.5 Hydrologic Parameters

Several lithologies or conditions may be represented within any layer. A summary of the model input parameters assigned to the various geologic units in the model is shown in Table 8-3.For example, areas of different hydraulic conductivity representing clinker areas along the outcrop and fracture zones within the coal appear in the layers that represent the zone of the upper Fort Union Formation (layers 7 and 9). The results of multi-well pumping tests in the Caballo Creek area (Appendix B) were generally used as starting points for estimates of permeability in any area. Data for pumping tests in the coal, particularly single-well or short-term tests, may not represent regional permeabilities, which tend to be dominated by major fracture zones in the coal. Accordingly, the range of permeability values used in the model was based primarily on matching to steady-state and transient-state conditions.

Table 8-3
Summary of Model Input Parameters for Caballo Creek

Formation	Model Layer	$K_{x,y}$ (ft/s)	K_z (ft/s)	S_s (1/ft)	S_Y (unitless)	Porosity (%)
Alluvium	1,2,3,4,5,6,7	.0003	3E-5	0.00003	0.2	25
Wasatch Discontinuous sands	2,3,4,5	1E-6 to 3E-6	2.5E-9 to 3E-7	2.4E-5	0.15	20
Wasatch Confining	6	3E-10	6E-11	1.5E-5	0.005	10
Upper Fort Union Coals	7,9	5E-6 to 1E-4	5E-7 to 4E-5	2.1E-6 to 7.9E-5	0.0005 to 0.004	1
Upper Fort Union Confining	8,9,10	3E-10	6E-11 to 1E-10	1.5E-5	0.005	10
Lower Fort Union Tullock	11	1E-6 to 2E-5	1E-7 to 2E-7	1.5E-5	0.01	20
Scoria	2,3,4,5,6	8E-5	1E-6	0.003	0.1	25

$K_{x,y}$ = hydraulic conductivity (horizontal)
K_z = hydraulic conductivity (vertical)
S_s = specific storage
S_y = specific yield

There are relatively few reliable data on storage coefficients in the PRB, but a compilation of values derived from multi-well pumping tests is included in Appendix B. The values for storativity used for the various model layers are summarized in Table 8-3. Storage coefficient values vary considerably, depending on whether the unit being tested is under confined or unconfined conditions. Most pumping tests conducted in the coal are considered to be under confined conditions. Storage coefficients derived from these pumping tests are in the range of 10^{-3} to 10^{-5}. The specific storage (S_s) (equivalent to the storage coefficient divided by the thickness) used for the coal ranged between $3.2x10^{-6}$ ft^{-1} and $6.4x10^{-6}$ ft^{-1}. Pumping tests conducted in the Wasatch sands may be under confined or unconfined conditions. Storage coefficients derived from these pumping tests are generally in the range of 10^{-2} to 10^{-4}. The specific storage derived from Wasatch sand tests averages $1.8x10^{-4}$ ft^{-1}.

8.6 Impacts of CBM and Mining on Groundwater Levels

The primary purpose of the Caballo Creek sub-area model was to provide good calibration data for the regional model within an area that has a long history of CBM development. The groundwater level drawdown in the developed coal unit (layer 7) for the year 2000 is shown in Figure 8-3. The modeled drawdown is reasonably consistent with actual drawdowns observed in BLM monitoring wells. Figure 8-4 shows the drawdown in the year 2000 for the deep Wasatch sandstone unit that overlies the developed coal. The sandstone is separated from the coal by as little as 40 feet of claystone.

A hydrograph that shows the modeled and actual drawdown in the developed coal and the overlying sandstone is shown in Figure 8-5. There has been extensive drawdown of more than 250 feet in the coal in the area of the BLM MP-22 monitoring well nest as a result of CBM pumping over the past 8 years. Drawdown in the sandstone has been apparent only in the past 3 to 4 years and is currently about 20 feet. Matching of model-projected drawdowns to actual drawdowns over an extended period provided the best information on the vertical permeability of the claystone confining layer that separates the coal from the overlying sandstone.

Figure 8-3 Drawdown of Groundwater Levels in Coal – Year 2000

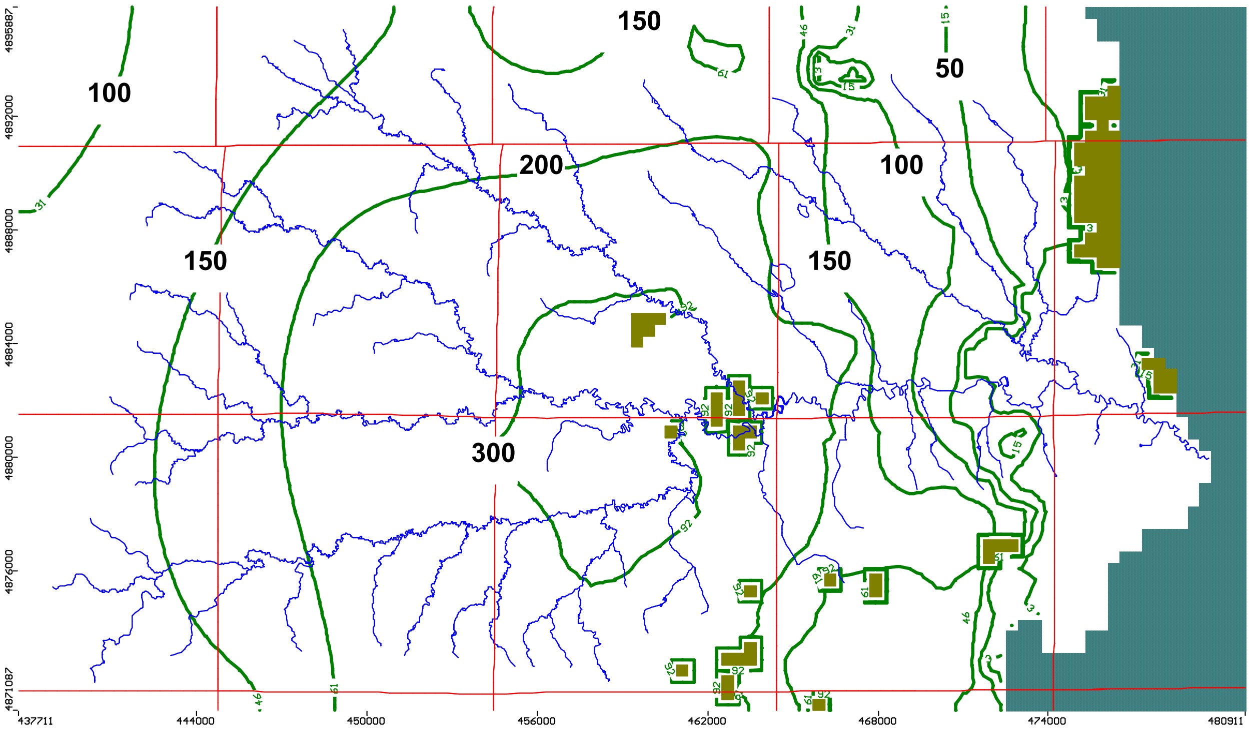


Figure 8-4 Drawdown of Groundwater Levels in Deep Wasatch Sandstone – Year 2000

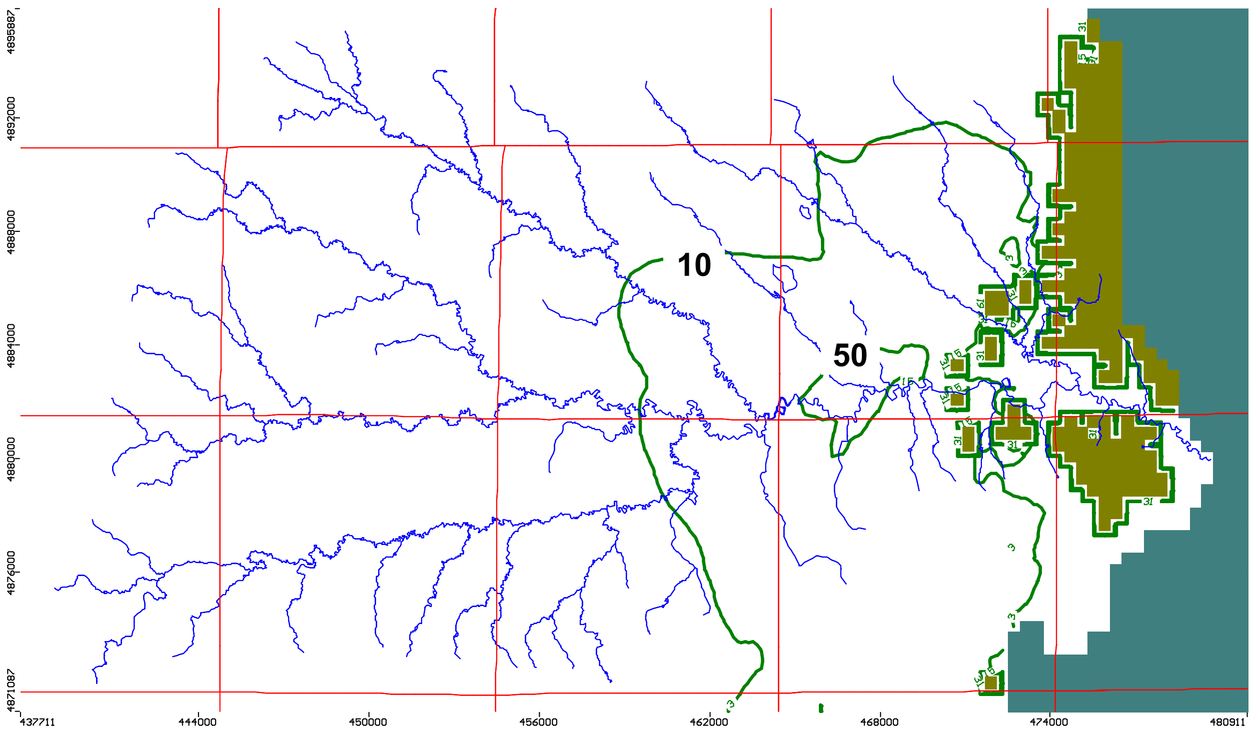


Figure 8-5 Modeled and Actual Hydrographs of Groundwater Levels in Coal and Sandstone