3.0 NUMERICAL GROUNDWATER MODEL

The Plant Site numerical model described in this report (current Plant Site model) is designed to serve as a tool to assess the effectiveness of the groundwater capture well system installed by PPLM at the Plant Site as well as provide a better understanding of the interactions between process ponds, groundwater, and surface water in the vicinity. The current Plant Site model includes refinements to the previous model (2008 Plant Site model) developed by Geomatrix (2008). The primary refinements include adjustments to model boundaries, layers, grid discretization, and assignment of model properties based on data collected both before and after the development of the 2008 Plant Site model (includes data collected through Spring 2014). The model geometry and discretization were also refined to more accurately simulate groundwater flow in distinct stratigraphic intervals. The conceptual model described in **Section 2.0,** above, provides the foundation for the refinements in the development and parameterization of the 2014 Plant Site model.

NewFields used hydrologic data sets from three distinct time periods for model design and calibration:

- Late 2003 – follows a period of below average precipitation, when groundwater capture rates were much lower than current rates.
- December 2003 through January 2006 – incorporates a period when a large transient aquifer stress occurred in the central portion of the Plant Site (breach of the Brine Pond D4, discussed in **Section 2.6.2** above).
- Early 2014 -- the recent most comprehensive data set available.

Following calibration, the model was used to assess the effectiveness of capture systems. The model code, design, and calibration of the Plant Site model are discussed below.

3.1 CODE SELECTION

The current Plant Site model was developed using MODFLOW-SURFACT Version 3, a groundwater modular code based on the U.S. Geological Survey modular groundwater flow model, MODFLOW (Hydrologic, Inc. 1998). MODFLOW-SURFACT was used because it allows for variable saturation. The USGS code MODPATH Version 3, (Pollock 1994) was used to assess capture by simulation of advective transport of constituents in groundwater. The commercial graphical-user-interface software Groundwater Vistas© (Version 6.67, Build 5) was used for model pre- and post-processing.

3.2 MODEL DOMAIN

The domain was expanded in the current Plant Site model to include additional relevant hydrologic features and recently collected hydrologic and lithologic data. The expanded domain for the revised model encompasses about 3,839 acres and extends approximately 16,000 feet in the east-west direction and 14,000 feet in the north-south direction (**Figure 35**). The current domain is about two times the size of the 2008 model domain. The revised model domain includes all process ponds at the Plant Site, East Fork Armells Creek, the Colstrip Townsite, and the Surge Pond. The domain extends from low hills approximately 1,700 feet south of the Plant Site to the Surge Pond and includes the floodplain of

East Fork Armells Creek about 2,500 feet north of the Sewage Treatment Ponds. The domain extends from the eastern most strip mine of Area A in Western Energy Company's Rosebud Mine on the west to reclaimed mine lands on the east. The model domain crosses the Surge Pond along a gentle flow divide visible in **Figure 14.**

The revised model domain was discretized (**Figure 36**) into 255 rows and 253 columns with 333,825 total active cells. The model grid telescopes from a uniform 100-foot spacing down to 25 feet in the area around the Plant Site process ponds. The finer grid-spacing provide greater horizontal discretization of the hydrologic properties and boundary conditions (including pumping wells), which provides greater detail in simulation of groundwater flow within the areas of greatest interest.

3.3 MODEL LAYERS

The revised model domain was subdivided into six layers, four more than the previous (2008) version. Layer bottom elevations were extrapolated based on contacts of lithostratigraphic units as described in **Section 2.1.2** and presented on **Figure 5**. In some areas, wells located outside of the model domain were used to extrapolate model layer elevations along the perimeter of the active model domain. Model layers that correspond to the assigned lithostratigraphic units are summarized (top to bottom) as follows:

1. Layer-1 – Fine-Grained Alluvium, Rosebud Coal, and Spoils
2. Layer-2 – Coarse-Grained Alluvium (sand and gravel), Rosebud Coal, and Spoils
3. Layer-3 – Interburden and East Fork Armells Creek Coarse-Grained Alluvium
4. Layer-4 – McKay Coal and East Fork Armells Creek Coarse-Grained Alluvium
5. Layer 5 – Shallow Sub-McKay (approximately 75 to 135 feet thick)
6. Layer 6 – Deep Sub-McKay.

The layer elevations extend from ground surface (top of Layer 1), at a maximum of 3,467 feet amsl, to the bottom of Layer 6 at an elevation of 2,950 feet amsl. Cross sections of the groundwater model layering and associated units are shown on **Figures 37** and **38**. These figures also show the previous model layering which grouped together many of the hydrostratigraphic units.

When using MODFLOW-SURFACT's variably saturated flow option, layer types must be defined as either Type 3 or Type 0. Model Layers 1 through 4 are simulated as Type 3 layers (convertible layers), which allow transmissivity to vary dependent on saturated thickness and simulate groundwater flow under either confined or unconfined conditions. Layers 5 and 6 are simulated as type 0 layers (confined layers), which is appropriate because the potentiometric surface does not cross below these layers during simulations.

3.4 BOUNDARY CONDITIONS

The groundwater flow system was established by assigning model boundaries to the model domain. Model boundaries coincide with natural hydrologic boundaries that include groundwater flow into and out of the active model domain, areas where groundwater flow is restricted, and areas of parallel groundwater flow. The boundaries established for the current Plant Site model are complex due to the many stresses affecting to the aquifer which create a complex flow field. **Figures 39** and **40** illustrate the assigned boundary conditions for Layers 1 through 3 and Layers 4 through 6, respectively.

NewFields used hydrologic data sets from three time periods described above (**Section 3.0**) to design boundary conditions for three calibration periods:

- 2003 Steady-State
- December 2003 through January 2006 transient
- 2014 Steady-State

Each of the three models has the same domain, layer configuration, and aquifer parameter distribution. The only boundary conditions that differ between the three calibration simulations are:

- Elevation values for head dependent boundary cells,
- Pumping rates assigned to wells, and
- Recharge rates.

Construction of the boundary conditions is discussed in detail below.

3.4.1 General Head Boundaries

The General Head Boundary (GHB) Package was used to represent the groundwater underflow into and out of the active model domain. A GHB is a head-dependent boundary where the flow into or out of the model is equal to the difference between the head in the model cell and the head at a distance from the model boundary times the estimated conductance of the GHB. The conductance is estimated by the following equation:

$$Conductance = WTK/L$$

Where:

W = *Width of cell*
T = *Saturated thickness of cell*
K = *Hydraulic conductivity*
L = *Distance to the assigned head value*

The boundaries were established far enough from the Plant Site area to minimize potential boundary influences on the model results (**Figure 39** and **40**). The width, saturated thickness, and hydraulic conductivity of each GHB cell were populated using Groundwater Vistas-computed boundary condition option, which populates each GHB cell with the actual width, saturated thickness, and hydraulic conductivity of that cell. The properties and elevations assigned to each GHB cell are shown in **Appendix G**.

The heads at the GHBs were established for the 2014 steady-state model from lines of equal head potential. The potentiometric surfaces described in **Section 2.4.1** were used to assign the boundary head values and estimate distances to the lines of equal head potential. The 2014 shallow potentiometric surface map was used to construct the GHBs for Layers 1 and 2. Heads assigned to Layer 3 GHBs were set two feet lower than those in Layers 1 and 2 to simulate the slight downward gradient observed between overburden/spoils/Rosebud and the underlying interburden. The 2014 McKay potentiometric surface map (**Figure 15**) was used to assign head values and distances to the

GHBs for Layer 4, and the shallow Sub-McKay and deep Sub-McKay potentiometric surface maps (**Figure 16** and **17**, respectively) were used to assign head values and distances to the GHBs of Layers 5 and 6, respectively. GHBs were assigned to match observed and inferred underflow into and out of the model domains as depicted on the potentiometric surface maps.

The GHBs for the 2003 steady-state model were constructed by adjusting the 2014 assigned boundary elevations based on a general comparison between head values from 2014 and 2003 in wells located inside and outside of the model domain near the relative boundaries. A list of wells and associated water levels used for the general comparison are shown in **Appendix H.** In general, head values in 2003 were lower than in 2014. The only exceptions are western and northern GHBs, which were assigned the same head values and distances as the 2014 steady-state model, and the southern GHB (at the Area B mine cut), which was assigned a higher head value. GHBs for the southern model boundary were established to simulate underflow through Layers 1 through 5 because, in 2003, the mine cut at that location was not being dewatered. The closest mine cuts in Area B of the Rosebud Mine were on a mining hiatus from 1987 through 2004 (Western Energy 2013a).

Available data outside the model domain for 2003 is sparse and, therefore, the potentiometric surfaces for 2003 were not drawn outside of the model domain and subsequently not used to assess GHB head values. Rather, the 2003 potentiometric surfaces confirmed that the flow field between the 2003 steady-state model and the 2014 steady-state model was similar. The GHB head values in the 2003 steady-state model were also used in simulation of the December 2003 – January 2006 transient model.

3.4.2 No-Flow Boundaries

No-flow boundaries were assigned along the perimeter of the active model domain where groundwater flow direction was assumed to be parallel to the model boundaries. The no-flow boundaries in the 2014 steady-state model were established from the respective potentiometric surface maps discussed in **Section 2.4.1,** above. The bottom of Layer 6 also represents a no flow boundary; however, no data have been collected to this depth. Rather, the boundary was set deep enough to minimize influence on model results. All no-flow boundaries are consistent between the models except the southern model boundary which, in 2014, has no-flow boundaries in Layers 3 and 4 due to dewatering of the overlying groundwater system, creating upward flow and minimizing horizontal flow. The no-flow boundaries were the same for the 2003 steady-state and 2004 and 2005 transient models.

3.4.3 River Package Boundaries

The River Package was used to simulate groundwater and surface water exchanges along East Fork Armells Creek and between the Surge Pond and the groundwater flow system (**Figure 39**). The River Package allows water to move into and out of the river cell based on the difference in water level between the groundwater and the stage in the surface water feature. A conductance assigned to the river cell restricts the flow rate exchange. The conductance is estimated by the following equation:

$$Conductance = KLW/D$$

Where:

K = *Hydraulic conductivity*

L = *Length of cell*

W = *Width of cell*

D = *Riverbed Thickness*

3.4.3.1 East Fork Armells Creek

Stream elevations from synoptic flows measured at gaging stations (**see Figure 2**) were used to assign stage elevations within the model. River Package cells were assigned elevations by dividing the length of East Fork Armells Creek in the model domain into five reaches, coincident with the location of the gaging stations. River Package elevations were assigned at the gaging locations based on surveyed elevations and extrapolated along the reaches between the gaging stations:

- Reach 1 - southwest model boundary to gaging station AR-5;
- Reach 2 - from station AR-5 to AR-4;
- Reach 3 - from station AR-4 to AR-3;
- Reach 4 - from station AR-3 to AR-2; and,
- Reach 5 -from station AR-2 to the northern model boundary.

River cell elevations at the upper end of Reach 1 and the lower end of Reach 5 were established by extrapolating a slope between the nearest stream gaging station and an elevation from the USGS topographic map.

River stages measured in 2014 were not used in the model because the 2014 data were collected during an unusually high spring runoff, while the model simulated a period of seasonally low water conditions. Instead, River Package cells were assigned stage values based on data collected during the 2012 synoptic gaging event. River stage values assigned to the 2014 steady-state model range from 3,252.7 to 3,197.3 feet amsl. River Package cells in the 2003 steady-state model were assigned the same elevations as the 2014 steady-state model. River Package cells in the transient model were assigned variable stage elevations, monthly based on water levels measured in well OT-7 which is adjacent to East Fork Armells Creek.

The simulated stream length parameter for each cell was assigned based on the length of the stream extending through the cell. The width of the stream in each river cell was assigned a value of three feet, which was estimated from aerial measurements and on-site observations. Site-specific data are not available for stream bed thickness and hydraulic conductivity. These parameters were assigned initial values of 1 foot and 1 foot/day, respectively based on the presence of shallow sediments in the area (silt and fine sand).

3.4.3.2 Surge Pond

The Surge Pond was also simulated using the River Package (**Figure 39**). Cells simulating the Surge Pond were assigned stage elevations based on elevations measured at similar times of year. The surface water in the Surge Pond was assigned an elevation of 3,281.1 feet amsl in the 2014 model. In the 2003 steady-state model and the 2004-2005 transient model, the Surge Pond was set to an elevation of 3279.7. The width and length of the stream cell was based on the model cell dimensions. The bottom elevation of the River Package cells in the Surge Pond was extracted from a USGS digital elevation model (DEM) of the original ground surface. Streambed thicknesses were estimated to be 2 feet and hydraulic conductivity was assigned an initial value of 1 foot/day (this parameter was subsequently adjusted to 4 feet/day during calibration). No site specific data are available for these parameters.

3.4.4 Barriers

MODFLOW's Hydraulic Flow Barrier (HFB) package was used to simulate two dams along the northeast and southeast boundary of the Surge Pond (**Figure 39**) and grouting beneath the dams described by Bechtel (1982). The thickness and hydraulic conductivity in the HFB package were estimated at 35 feet and 10^{-4} feet/day, respectively.

3.4.5 Wells

Groundwater capture wells and water supply wells were represented using both the Well and the Fracture-Well (FWL5) packages. The FWL5 package was used as it has several characteristics that the regular Well package does not have, including: (1) the well pumping rates are automatically allocated between layers penetrated by the well screen, (2) when the level in the well drops below the bottom of the layer, the pumping rates are automatically reallocated to lower layers, and (3) if the water level drops below the pumping level, the flow rate is decreased until the pumping level is maintained. Use of the FWL5 package can cause instability. As a result, wells causing model instability were changed to Well package wells. Pumping rates for Well package wells completed across multiple layers were distributed based on the pumping distribution determined when simulated as a FWL5 well. Locations of FWL5 wells and Well package wells are shown in **Figures 39** and **40**.

3.4.6 Drains

Both the underdrain system installed below Fly Ash Pond B and below Units 1 & 2 Bottom Ash Clear Well were simulated in the 2014 steady-state model using the Drain package. Drain cells remove water based on the hydraulic conductivity and the difference between the water level in the aquifer and the assigned drain elevation. Flow into and out of drain cell is restricted by the conductance term calculated using the same equation to calculate conductance in the river package. The drains were constructed using engineering drawings containing the elevations of drain pipes. Drain cells representing the Fly Ash Pond B underdrain were assigned varying elevations.

The location of the drain pipes were approximated by geo-referencing the engineered drawings supplied by PPLM. Drain Package cells were assigned to locations where underdrain pipes are located. Each drain cell was assigned to be the length in which the drain was digitized in the occupied cell, a width of 1 foot, a thickness of 1 foot, and a hydraulic conductivity of 25 feet/day. Drain Package cell conductance was then adjusted during calibration. The layout of the drains in the model is shown in **Figure 39**.

The Fly Ash Pond B was undergoing excavation in late 2003 to prepare for underdrain system installation. The drain cells in the 2003 model were assigned a drain elevation of the lowest dewatered elevation targeted during construction and installation based on information supplied by PPLM. The construction and installation of the Fly Ash Pond continued until the drain was made operational in March 2005.

3.4.7 Recharge

Figure 41 is a map showing the various recharge zones that were established throughout the model domain to simulate net infiltration and seepage from water storage and process ponds. In the model, Recharge package cells were assigned values representing net recharge (infiltration – evapotranspiration) Recharge areas were grouped and spatially assigned as described in **Section 2.7.3**. These areas include background, lawn-irrigated areas, surface exposures of clinker, unvegetated areas, and impervious areas. Additional recharge was added in and around Units 1 & 2 based on previous calibration (Geomatrix 2008) representing a suspected leaking drainpipe in the sub floor of Unit 3 (Holzwarth 2008).

Recharge zones for the process ponds were refined based on aerial photographs. Seepage from the following ponds (described in **Section 2.3.5 and 2.7.2**) were assigned different recharge zones: (1) Units 1 and 2 Pond A, (2) Units 1 and 2 Pond B *(set to 0),* (3) Units 1 and 2 Clearwell *(set to 0)*, (4) Units 1 and 2 Bottom Ash Pond, (5) Units 1 and 2 Brine water Disposal Ponds (D-1 through D-4), (6) Units 1 and 2 Colling Tower Blowdown Pond (Pond C), (7) Units 3 & 4 Wash Tray Pond, (8) Units 3 & 4 Drain Collection Pond, (9) Units 3 & 4 Bottom Ash Ponds, (10) Units 3 & 4 North Plant Area Drain Pond, (11) Units 1-4 North Plant Area Sediment Pond, (12) Units 1-4 Sediment Retention Pond, (13)Various WECO Ponds, and (14) City of Colstrip Sewage Lagoons.

Initial recharge estimates were assigned to the model based on the conceptual model estimates and were adjusted during calibration.

3.5 AQUIFER PARAMETERS

Aquifer parameters assigned in the model consist of hydraulic conductivity, aquifer storage, and effective porosity. Parameter values were assigned to model cells based on the hydrostratigraphy of the subsurface delineated for the conceptual model described in **Section 2.1.3** and presented in **Figures 4** and **5**. Geometric mean hydraulic conductivity values from field tests collected for the various hydrostratigraphic units and summarized in **Section 2.1.4** were assigned to the various hydrostratigraphic units in the model as initial estimates. Hydraulic conductivity zones representing lithologic units were further subdivided during calibration and the values assigned to these zones were adjusted within the measured ranges in order to meet calibration goals. The final calibrated hydraulic conductivity is described in **Section 4.0**.

Transient model simulations require assignment of aquifer storage parameters. Particle tracking (presented in **Section 6.0**) requires assignment of effective porosity values. Aquifer storage includes specific yield and storativity properties. Specific yield is a property of unconfined aquifers and storativity is a property of confined aquifers. Specific yield, storativity, and effective porosity values assigned to the model were based on material properties described in the available well logs. Ranges of values for specific yield and effective porosity based on literature for the various lithologic units are presented in **Table15.** Storativity of confined aquifers is 0.005 or less (Fetter 1994). The calibrated storage parameters are described in **Section 4.0.**

Table 15. Summary of Specific Yield and Effective Porosity Values from Literature

	Specific Yield Range	Specific Yield Reference	Effective Porosity Range	Effective Porosity Reference
Gravelly Sand	0.2-0.35	Fetter (1994)	0.2-0.35	Domenico & Schwartz (cited in table 2, page 11 of Lovanh et al. 2000)
Silt	0.03 – 0.19	Fetter (1994)	0.01-0.3	Domenico & Schwartz (cited in table 2, page 11 of Lovanh et al. 2000)
Clay	0-0.05	Fetter (1994)	0.01-0.2	Domenico & Schwartz (cited in table 2, page 11 of Lovanh et al. 2000)
Siltstone	0.009 -0.327	Morris and Johnson (1967)	0.01-0.35	Domenico & Schwartz (cited in table 2, page 11 of Lovanh et al. 2000)
Coal	No reference	No reference	0.008-0.094	Brown and Parizek (1971) (cited page 39 in Hawkins (1995))
Spoils	0.006 – 0.352	Collier (1964)	0.138-0.164	Hawkins (1995) page 39
Fine Grained Sandstone/Sandstone and Siltstone	0.021 – 0.396	Morris and Johnson (1967)	0.01-0.4	Domenico & Schwartz (cited in table 2, page 11 of Lovanh et al. 2000)

4.0 MODEL CALIBRATION

Model calibration involves finding a combination of boundary conditions, input parameters, and stresses that generate head and flux values throughout the model that match field-measured head and flux values and achieve the calibration goals, as outlined above. Groundwater model development and calibration were conducted in general accordance with standard industry practices, such as protocols described in Anderson and Woessner (1992).

Following construction of the model framework and boundaries and assignment of initial model parameters, the Plant Site model was calibrated to provide a measure of confidence in its ability simulate groundwater flow and meet project objectives. The calibration process requires first establishing a set of calibration targets and goals. Model inputs were then adjusted iteratively within the model to achieve a reasonable match between observed and simulated target values. The quality of the match was judged using both quantitative and qualitative methods.

Model calibration is the process of adjusting uncertain input parameters within reasonable ranges to reduce the difference between measured and simulated target values. It should be noted that achieving calibration does not guarantee the set of input parameters selected is unique and that other plausible inputs would not achieve similar calibration results. However, calibration and verification to several independent sets of both steady-state and transient target data increases confidence in the model's capability to simulate groundwater flow under a variety of aquifer conditions.

4.1 DEVELOPMENT OF CALIBRATION TARGETS AND DATA SETS

Both qualitative and quantitative targets were developed for calibration. Qualitative targets included potentiometric surface maps that were developed based on measured groundwater elevations, hydrographs of groundwater elevations over time, and time-drawdown plots from aquifer tests.

Quantitative targets used to calibrate the current Plant Site model include: measured water levels, estimated flux into and out of the groundwater system as underflow, and net gains and losses in East Fork Armells Creek. The following independent steady-state and transient hydrologic data sets were used to establish quantitative targets:

<u>Steady-State</u>

- Heads and fluxes for the period of October through December 2003
- Heads and fluxes for the period of January through March 2014

<u>Transient</u>

- Time-drawdown during pumping test of capture well 78A
- Time-drawdown during pumping test of capture well 78A and 82A
- Heads and fluxes measured between December 2003 and January 2006

4.1.1 2003 Steady-State Calibration Data Set

Head targets for the 2003 steady-state model were established from water levels measured in the fourth quarter of 2003 (October through December). The water level data set was taken from a period following relatively low precipitation and fairly stable groundwater elevations. This period also represents a period when average groundwater capture rates were less than half of current rates. To establish a set of water levels that represented that time frame, the largest synoptic water level data set was first identified (early December 2003). To provide for greater spatial coverage, the early December dataset was augmented with additional water level data collected during other times during the fourth quarter of 2003. A total of 131 head targets were used in the 2003 steady-state model. **Appendix I** contains the observed head targets identified and the date of the measurements. Well screens completed across multiple model layers were located vertically within the model, based on the elevation of the center of well screens.

The calculated fluxes associated with the water budget for the December 2003 data set were used as flux targets for the 2003 steady-state model. The water balance included estimates of groundwater underflow, pond seepage, background areal recharge, groundwater extraction (from drains and wells), and net flow loss and gain estimates between East Fork Armells Creek and the groundwater system. A description of the components of water balance using the December 2003 data is included in **Section 2.7**.

In addition to the target head and flux data, the 2003 potentiometric surfaces discussed in **Section 2.4.1** were used to qualitatively evaluate model calibration based on the observed closeness of fit between simulated and observed potentiometric surfaces maps.

4.1.2 Transient Calibration to Aquifer Test Data

Multiple-well pumping tests performed by Hydrometrics (2007) in wells 78A and 82A were simulated as a check on the ability of the model to accurately simulate hydrologic conditions in that area. Time-drawdown plots for observation wells were used as transient calibration targets for the pumping tests. Observation well data for two wells (43S and 44S) were available for the well 78A pumping test and observation well data for one well (81A) was available for the well 82A pumping test.

4.1.3 December 2003 – January 2006 Transient Calibration Data Set

The calibration data set for the 2004-2005 transient model included head targets from measured water levels obtained from December 2003 through January 2006. The data set was matched qualitatively by comparing measured and simulated hydrographs at monitoring points. A total of 82 target locations with a total of 1,369 target head values were used in the 2004-2005 transient model.

4.1.4 2014 Steady-State Calibration Data Set

The head targets for the 2014 steady-state model were established from water levels measured in the first quarter of 2014 (January through March). The water level data set was taken from a time which exhibited relatively low precipitation and fairly stable groundwater elevations when transient stresses were at a minimum. To establish a set of water levels best represented during that time frame, the most comprehensive synoptic groundwater level data set was first established (February, 2014). The head target dataset was augmented with additional groundwater level data measured at other times in the first quarter of 2014 to provide greater spatial coverage. Again, to provide for greater spatial coverage in the data, additional groundwater levels measured outside the first quarter of 2014 were also used to provide more spatial coverage in key areas where 2014 data were not available. These areas include water levels for Townsite wells generally from December 2012 and water levels in a few wells near East Fork Armells Creek from October and December 2013. A total of 165 head targets were used in the 2014 steady-state model. **Appendix J** presents the observed head targets and the dates of the measurement. Well screens completed across multiple model layers were located vertically based on the center of well screen elevations.

The calculated fluxes of the pre-model water balance for February 2014 were used to help calibrate the 2014 steady-state model. The water balance included estimates of groundwater underflow, pond seepage, background areal recharge, groundwater extraction (from drains and wells), and net flow loss and gain estimates between East Fork Armells Creek and the groundwater system. A description of the components of water balance for December 2014 is discussed in **Section 2.7**.

In addition to the target head and flux data, the 2014 potentiometric surfaces discussed in **Section 2.4.1** were used to visually calibrate the observed closeness of fit between simulated and observed potentiometric maps.

4.1.5 Calibration Goals

A set of both quantitative and qualitative criteria was established as goals to assess how well the model was calibrated. Steady-state and transient goals for the steady-state models are summarized below.

Steady-State Model Goals

- The absolute residual mean of target head values (average absolute difference between simulated and target head values) should be less than 2.0 feet (Quantitative);
- The residual mean of target head values (average head difference between simulated and target head values) should be close to zero (Quantitative);
- The residual standard deviation divided by the range in head values should be less than 10 percent (less than 5 percent for a well-calibrated model) (Quantitative);
- Residuals (difference between observed and simulated head) should be plus or minus 5 feet (Quantitative);
- Simulated groundwater flux into and out of the model along East Fork Armells Creek should be within the range of flux estimated as part of the water balance (Quantitative);
- Visual observations should reveal the simulated and observed potentiometric maps are a close fit (Qualitative).

Transient Model Goals

- Residual statistics should fall within criteria established for steady-state calibration described above (Quantitative).
- Visual observations of simulated and observed hydrographs and simulated and observed time-drawdown should reveal similar water level changes in timing and magnitude (Qualitative).

4.2 CALIBRATION PROCESS AND RESULTS

Model calibration was initiated after establishing calibration goals and targets. During calibration, different input parameters were varied within a range of values determined based on field measurements and literature values presented in **Section 2.0** (Conceptual Model). Results of each calibration run were then evaluated to determine if the input parameter adjusted during that run achieved a better or worse match to calibration targets. This was evaluated using both quantitative and qualitative methods.

Quantitative methods included calculating residuals for each quantitative target in the model. Residual is simply the difference between the model simulated and the observed target values. Calibration statistics are then calculated for each model run. These statistics provide a measure of overall match between simulated and observed conditions. Qualitative methods included visually comparing potentiometric surface maps or hydrographs generated by the model to those based on target values. The quality of the match was then judged by the modeler (Anderson and Woessner 1992).

More emphasis was placed on evaluating measured heads and measured stream gains and losses during calibration than on estimated fluxes, such as groundwater underflow. Changes made to non-transient inputs that improved calibration statistics in one of the four calibration schemes were subsequently applied to the model for use in the other three calibrations. If the changes improved calibration in all four schemes evaluated, the changes were made and the calibration process continued.

Model calibration was achieved using a combination of manual and automated methods. PEST software (Doherty 2005) was used to some degree to help with automated calibration. However, convergence issues limited the value of this software. Most of the automated portion of the calibration process was achieved using the auto-sensitivity tool in Groundwater Vista used help to optimize values of hydraulic conductivity, riverbed conductance, and pond seepage.

Input parameters, which were varied during calibration are listed in order of importance to model calibration as follows:

- Hydraulic Conductivity (varied within ranges described for each lithostratigraphic unit [See **Section 2.1.4**]).
- Pond Seepage (varied within ranges estimated in the water balance discussion [see **Section2.7**]).
- Background Recharge (varied within estimated range provided in the water balance discussion [see **Section2.7**]).
- Conductance of Head-Dependent Boundaries (varied within ranges for each lithostratigraphic unit).
- Storage (only adjusted in transient calibration) (varied within ranges reported from aquifer tests [**Appendix A**] and literature values for similar lithologies).
- Stage in the East Fork Armells Creek (only adjusted during transient calibration).

The most frequently adjusted parameters during model calibration were hydraulic conductivity and recharge because it was clear during the calibration the model was most sensitive to these parameters. Seepage rates from process ponds were adjusted more frequently than net recharge rates for most areas because seepage rates represented the largest source of recharge within the Plant Area and have a greater effect on water levels in individual wells in the Plant Site where well densities are greater. In addition, net recharge rates for unvegetated areas were adjusted more frequently than rates for other zones.

Areas of hydraulic conductivity and recharge that were most sensitive during model calibration were selected for sensitivity analysis as discussed below in **Section 5.0.** Hydraulic conductivity values assigned to head-dependent boundaries were also adjusted during the calibration process but to a much lesser degree. These included values in Drain Package cells, River Package cells representing East Fork Armells Creek and the Surge Pond, and GHBs. During transient calibration, recharge rates and storage parameters were adjusted most frequently. Particle-tracking was periodically performed to check the match between simulated and observed transport of process pond-affected groundwater.

Model calibration suggested that increases or decreases in the GHB hydraulic conductivity generally resulted in an increase or decrease of flow into the model, respectively. An increase or decrease in flow into the model boundaries typically resulted in an increases or decreases in water levels in area closest to the model boundary. The GHBs most sensitive to change were typically those located on the western, northern, and eastern bounds of the model. With the exception of the area just downgradient of the Surge Pond, the model did not appear to be sensitive to changes in the conductance of River Package cells simulating the Surge Pond. Increasing the conductance of River Package cells in a gaining stream reach resulted in a decrease in water levels and an increase in flow from the groundwater to the river. On the contrary, decreasing the conductance along a losing reach typically result in a decrease in water levels and a decrease in flow from the river boundary to the groundwater system.

4.2.1 Calibrated Parameter Distributions

Figures 42 through **47** show the final calibrated distribution of hydraulic conductivity zones for Layers 1 through 6, respectively**. Appendix K** presents the horizontal hydraulic conductivity (Kx) and vertical hydraulic conductivity (Kz) values, corresponding lithologic unit for each of these zones, model layers, and Kz:Kx anisotropy ratio. Calibrated Kx and Kz values are the same for all model calibration periods. Final calibrated Kx values fall within the estimated range of values from Colstrip testing for the corresponding hydrostratigraphic units **Table 16,,** with one exception: the value (15 feet/day) for a small area of McKay coal northwest of the north Cooling Tower Blowdown Ponds C (**Figure 45**). However, this value which still falls within values for coal in the Fort Union Formation.

There is a large degree of variability in the Kz:Kx ratios in the model. Kz:Kx ratios in the model are typically supported by literature values. For example, Todd (1980) reported Kz:Kx can range from 0.1 to 0.001 in alluvium. Anisotropy ratios of shales can range from 0.5 to 0.0002 depending on the scale measured (Cosan et al., 1994) and are also reported to range from 0.00082 (formations with thick and frequent shales) to 0.01 (sandstone formations with short thin and frequent shales; Burton and Wood, 2013).

In the Fort Union Formation, anisotropy is greatly influenced by bedding planes and the sedimentary processes that formed interfingered sandstone, shale, mudstone and coal strata. The Kz of a section of the Fort Union Formation is primarily controlled by the layer with the lowest Kz and its degree of lateral continuity, whereas the horizontal hydraulic conductivity will be controlled by the higher permeable units. Nicklin Earth and Water (2014) estimated Kz:Kx in some of the Fort Union interbedded sandstone and mudstone units of as low as 4.37 x10-7. However the presence of vertical fractures can greatly influence the anisotropy of the bedrock layers.

Table 16. Final Calibrated and Measured Horizontal Hydraulic Conductivity Values

	Calibrated Horizontal Hydraulic Conductivity of Zones Representing Various Aquifer Materials			Hydraulic Conductivity as Summarized in Table 2		
Aquifer Material	Min	Max	Geometric Mean*	Min	Max	Geometric Mean
Alluvium	2	20	8.34	0.15	355	18.3
Coarse-grained Alluvium	30	250	83.64	----	----	----
Fine-grained Alluvium	0.2	0.7	0.37	----	----	----
Colluvium	0.2	0.2	0.20	----	----	----
Clinker	100	100	100.00	----	----	----
Fine Grained Alluvium/Colluvium	0.004	7	0.59	----	----	----
Fill	6	6	6.00	0.01	622	7.5
Overburden	0.25	0.25	0.25	----	----	----
Rosebud	12	12	12.00	0.9	65	12.5
Interburden	0.02	1	0.20	0.02	39	1.1
McKay Coal	1	15	4.48	0.06	9.3	2.3
Spoils	0.1	500	5.21	0.01	622	7.5
Sub-McKay	0.1	4	0.84	0.03	242	2.5
Deep Sub-McKay	2	2	2.00	----	----	----

* This is the geometric mean of the zone values used to represent this material in the model. It is not weighted spatially.

Anisotropy will typically vary between different hydrostratigraphic units. The shallow and deep Sub-McKay zones are represented by Layers 5 and 6, respectively. The shallow and deep Sub-McKay units have a similar range of Kx, dictated by whether there are greater amounts of sandstone or shale/mudstone. In the model, Layer 5 is assigned a greater Kz than Layer 6. It was necessary to assign lower Kz in Layer 6 in order to match measured vertical hydraulic gradients between the shallow and deep Sub-McKay; groundwater elevations in Layers 5 and 6 differ by more than 100 feet (**Figures 16** and **17**). This may be explained by the presence of thicker, more continuous low permeability layers (shale/mudstone) in the deeper Sub-McKay and thicker more continuous packages of sandstone in the shallower Sub-McKay.

Calibrated storage values (**Table 17**) are within estimated ranges of values (see **Section 3.5**). Final calibrated storage values are the same for all model calibration periods.

Table 16. Final Calibrated Storage Parameter Values

Unit	**Storativity (unitless)**	**Specific Yield (unitless)**
Fine-grained alluvium	3×10^{-5}	0.05-0.1
Coarse-grained alluvium	3×10^{-5}	0.1
Spoils	1×10^{-4} to 5×10^{-3}	0.1-0.2
Interburden	5×10^{-5}	0.01
Rosebud Coal / McKay Coal	5×10^{-5}	0.25
Sub-McKay	5×10^{-5}	0.05

Field measurements quantifying the streambed characteristics were not available for East Fork Armells Creek. Although a uniform conductance was initially used, varying stream conductance resulted in a better calibration. The River Package cell conductance was adjusted on a reach-by-reach basis during model calibration to produce simulated flow into and out of East Fork Armells Creek within acceptable limits (**Table 6, Section 2.7**) in the steady-state model and to produce adequate simulated water level changes in wells near East Fork Armells Creek in the transient model. As described in Section 3.4.3, the conductance was calculated from the stream width, length, hydraulic conductivity, and thickness. Hydraulic conductivity adjustments were used to calibrate this term; however, adjustment to any component of this term could have been used. Assigned parameters and elevations for the River Package cells are shown in **Appendix L**. The final calibrated hydraulic conductivity of the streambed in each river cell ranged between 0.3 and 10 feet per day. Specifically, hydraulic conductivity values ultimately developed included the following:

- Reach-1: 3 feet per day,
- Reach-2: 10 feet per day,
- Reach-3: 1.2 feet per day,
- Reach-4: 0.3 feet per day, and,
- Reach-5: 10 feet per day.

The River Package conductance cells simulating the Surge Pond was adjusted a during model calibration to until there was a reasonable match with estimated seepage rates (Table 6, Section 2.7). The final calibrated hydraulic conductivity of the Surge Pond river cells was 4 feet per day. The final calibrated river cell conductance values were applied to all model calibration periods.

The drain cell conductance of both Units 1 & 2 Pond B and below Units 1 & 2 Bottom Ash Clear Well underdrains were adjusted until the model simulated flows to the drain similar to measured flows at the Units 1 & 2 Pond B summarized in **Table 13** (**Section 2.7**).

The calibrated drain cell hydraulic conductivity of both Units 1 & 2 Pond B and below Units 1 & 2 Bottom Ash Clear Well underdrains was 10 feet/day. Calibrated hydraulic conductivities for the GHBs are generally the same as the hydraulic conductivity of the surrounding aquifer materials. The calibrated drain cell and GHB hydraulic conductivity developed were applied to all model calibration periods.

4.2.2 2003 Steady State Calibration

A total of 29 pumping wells were simulated as actively pumping in the 2003 steady-state model. The pumping rates for these wells were established as the average pumping rates for the fourth quarter of 2003 as presented in **Section 2.8.** **Table 13** shows the pumping rates used in the model. Additionally, certain drain cells located proximal to Units 1 and 2 Pond B were represented in the model as dewatering during excavation of this pond.

Recharge rates used in the 2003 steady-state model are presented in **Figure 48**. The rates ranged from 5.6×10^{-5} to 5.1×10^{-1} feet/day. These rates applied over the respective areas resulted in an inflow within the range of estimated inflow for background recharge and pond seepage.

Appendix I contains calibration statistics resulting from the 2003 steady-state model, based on 131 head targets. All head target statistics and the other general components of the water balance met the steady-state model calibration goals. Further, visual comparison of the simulated and observed potentiometric maps show that, in general, groundwater flow directions and gradients were similar.

4.2.2.1 2003 Calibration to Head Data

The calculated residual mean of target head values for all target wells was 0.02. The industry standard is that this value should be as close to zero as possible (Anderson and Woessner 1992). The absolute residual mean of the target head values was 1.46 feet, which meets the calibration goals of less than 2 feet. The residual standard deviation divided by this range was about 2.3%. Industry standards are that this value should be less than 10 percent and less than 5 percent for a well calibrated model (Anderson and Woessner 1992). All calibration targets for head were less than plus or minus 5 feet. The maximum residual was 4.68 feet and the minimum residual was -3.87 feet. **Figure 49** is a plot showing observed vs. simulated heads demonstrating that observed and simulated heads were randomly distributed on either side of the regression line, indicating the model is well-calibrated (Anderson and Woessner, 1992).

Figures 50 through **55** are maps showing the simulated potentiometric surfaces for Layers 1 through 6, for the 2003 steady-state calibration. Comparison of the computed potentiometric contours to those based on field measurements (**Figures 10** through **13**) indicates a good match between simulated and observed heads and gradients.

Residuals at each target location are posted on **Figures 50** through **54**, with positive (blue) values indicating the simulated head is less than the observed head and negative (red) values indicating the simulated head is greater than the measured value. The residuals posted on these figures allow for a spatial analysis of the calibration. One area where the 2003 simulation over-predicts heads is in the central portion of the model west of Units 1 & 2 A Pond and Sediment Retention Pond in Layers 1 and 4. Spatial bias in this area is discussed further in **Section 4.1.5** below. The 2003 simulation under-predicting heads beneath the D1 – D4 Brine Ponds in Layers 3 & 4. This could be an indication that recharge through this portion of the model domain was under-represented or that the model was under-representing the degree of vertical communication between groundwater in spoils and Rosebud Coal and underlying interburden and McKay Coal.

Another way to review the calibration spatially is to review the statistics by layer (**Table 18**). Calibration statistics indicate that model layers exhibit some spatial bias. Bias refers to the tendency to over- or under-estimate the value. Based on mean residuals, Layers 1 and 5 have slightly over-estimated groundwater elevations, while in Layers 2, 3, and 4, they are slightly underestimated. .

Table 17. 2003 Calibration Statistics by Layer

Layer	Absolute Residual Mean	Residual Mean
Layer 1	1.49	-0.61
Layer 2	1.29	0.12
Layer 3	1.35	0.74
Layer 4	1.38	0.65
Layer 5	2.32	-0.35

4.2.2.2 2003 Calibration to Flux Data

The components of the 2003 steady-state water balance were compared to the components of the estimated water budget to ensure the model simulation incorporated the appropriate rates of flux. **Table 19** presents estimated groundwater flux values along with corresponding simulated groundwater flux values. All the simulated flux values fall within the estimated ranges. **Appendix I** contains the groundwater model water balance resulting from the calibrated 2003 steady-state model.

Table 19. Comparison of Estimated and Simulated Groundwater Flux for 2003

	2003						2003 Steady State Groundwater Model Simulated Water Balance	
	Min (ft^3/d)	Max (ft^3/d)	2003 Estimate (ft^3/d)	Min (gpm)	Max (gpm)	2003 Estimate (gpm)	(ft^3/d)	(gpm)
Inflows								
Underflow In	28,365	113,462	56,731	147	589	295	34,449	179
PPL Pond Seepage	1,830	178,489	18,089	10	927	94	26,302	137
WECO Ponds Seepage	7,567	75,674	23,930	39	393	124	14,106	73
Sewage Lagoons Seepage	16,888	26,738	22,517	88	139	117	24,966	129
Surge Pond Seepage	4,113	41,132	13,007	21	214	68	8,440	44
Recharge (net infiltration)	12,648	21,080	16,864	66	109	88	19,054	99
Outflows								
Underflow Out	27,186	81,559	54,372	141	424	282	51,997	270
Outflow to E.F. Armells Creek	33,209	55,348	44,278	173	288	230	-44,301	230
Groundwater Extraction	25,145	38,812	30,554	131	202	159	27,663	144

The simulated pattern of outflow to East Fork Armells Creek was similar to that observed. Specifically, minimal outflow to the creek between surface water stations AR-5 and AR-4 and significant outflow to the creek downs stream of station AR-2, were simulated. **Table 20** presents the simulated flux from groundwater to East Fork Armells Creek

Table 20. 2003 Simulated Flow from the Groundwater System to East Fork Armells Creek

	Reach 1 (Domain to AR-5)	Reach 2 (AR-5 to AR-4)	Reach 3 (AR-4 to AR-3)	Reach 4 (AR-3 to AR-2)	Reach 5 (AR-2 to Domain)
Flow to East Fork Armells Creek from Groundwater. (GPM)	14.5	4.3	80.4	30	100

The estimated average groundwater extraction rate in the fourth quarter of 2003 was 159 gpm. The simulated extraction was slightly lower than this (144 gpm) due to the FWL5 package diminishing flow rates to a few wells.

4.2.3 Transient Calibration to Aquifer Test Data

Well pumping analyses performed by Hydrometrics (2007) in wells 78A and 82A were simulated as a check on the ability of the model to accurately simulate hydrologic conditions in that area. Drawdown vs. time plots for observation wells were used as transient calibration targets.

Data available for calibration simulations include a single estimated pumping rate for each well and drawdown data recorded at regular intervals from observation wells. Observation well data for two wells, (43S, 75 feet from the pumping well) and (44S, 85 feet from the pumping well) were available for the 78A pumping test. Drawdown data for well 43S was recorded at 30 second intervals for the duration of the 100-minute period of pumping and for 100-minute recovery period. Observation data for well 44S included drawdown recorded at 5 and then 10 minute intervals for the duration of the 100 minute test and for 100 minutes of recovery. Observation well data for one well, 81A at a distance of 79 feet was recorded during the start-up pumping at well 82A. Observation data for well 81A included drawdown recorded at 5 minute intervals for 10 days.

Transient models were designed using starting heads from the 2003 steady-state model. The 78A model ran for 300 minutes using automated time steps. The 82A model ran for 10 days using automated time steps. During calibration hydraulic conductivity and aquifer storage were adjusted.

Figures 56 and **57** display simulated and observed drawdown during pumping of wells 78A and 82A, respectively. Simulated drawdown curves generally match the timing and magnitude of measured drawdown.

4.2.4 Long-Term Transient Calibration

The model was also calibrated using head and pumping rates for the period from December 2003 through January 2006. Several events occurred during this time-period that effected groundwater flow in the Plant Site area. The long-term transient simulation included 26 stress periods representing the 26 months from December 2003 through January 2006. Each stress period was divided into 10 time steps. The transient events that occurred in this period included changes in Plant Site process water management, installation of an underdrain below Units 1 and 2 Pond B, and the breach of Brine Pond D4. The 2003 steady-state model provided the initial conditions for the December 2003 through January 2006 transient model. Head value outputs generated by the 2003 steady-state model were used as initial heads for the transient calibration.

Pumping wells were simulated using average monthly pumping rates from the period between December 2003 and January 2006. **Appendix M** shows measured and simulated pumping rates for all capture system wells and other pumping wells during this period. Units 1 and 2 Pond B underdrains were activated in September 2004 (stress period 10 in the model). Hydrographs for wells throughout the model domain were used as calibration targets. Model inputs were adjusted in an iterative manner to improve the match between hydrographs based on field-measured data and those simulated by the model.

Recharge was a major parameter that was adjusted during the transient modeling to calibrate to the changing water levels at the wells used in the transient model. During the transient run, the hydrographs of the wells showed various responses to different, often unknown, recharge events.

These various events were likely caused by changes in surface water and plant water routing, storm water retention in response to precipitation and snowmelt runoff, and changes in mine water management practices. To calibrate the various hydrographs to changes induced from both pumping and recharge, pumping influences were first determined by maintaining constant recharge in the area. Once the model was run with constant recharge for an area, pumping influences could be detected in hydrographs. Transient recharge was then introduced to these areas to affect water level increases and decreases in the hydrographs. An attempt was made to match both the timing and magnitude of observed water level changes. Final recharge values are presented in **Appendix N.**

In addition to calibrating to the unknown recharge events, various other known recharge events occurred that induced stress on the aquifer. In October 2005, a breach was discovered in the liner of Pond D-4 resulting in a release of pond water and an increase in groundwater elevations in several surrounding wells (Hydrometrics 2007). The D-4 pond was simulated with zero recharge to represent its intact liner and, starting from September 2005, the breach was simulated through injection wells followed by an increase in recharge at the D-4 Pond. PPLM personnel drained the D-4 Pond and initiated pumping in several wells (B-1, B-4, B-5, 19SP, 26SP, 29SP, and 70SP) to minimize migration of impacted groundwater following discovery of the breach. **Appendix N** lists the calibrated monthly recharge values used for the 2004-2005 period for all the zones shown in **Figure 41.** Overall, 24 of the 40 recharge zones were adjusted to simulate transient recharge. **Appendix O** presents a table that outlines transient events and the model design used to simulate the event.

As part of the transient calibration, river stage values were also varied to reflect the temporal head changes observed at wells located in close proximity to East Fork Armells Creek. Monthly stage data for East Fork Armells Creek were not available; therefore, head changes at OT-07 were used to reflect changes in river stage.

Simulated and field-measured hydrographs are displayed on **Figures 58** through **62** for the layers with observed data (Layers 1 through 5). The degree of fit was assessed primarily qualitatively by visual assessment of the match between simulated and observed hydrographs. When reviewing these hydrographs, the match of overall trends (increasing/decreasing) and the match to the short-term transient D-4 breach and subsequent pump-back operation were judged as most important. However, the overall match of average value was also considered and the number of measured groundwater elevation measurements at each site was taken into account.

Hydrographs for wells 18SP, 26SP, 19SP, 41SP and 29SP in Layer 1 (**Figure 58**) and B-2 in Layer 2 (**Figure 59**) show that the model is capable of simulating the magnitude and timing of mounding that occurred in response to the D4 liner breach. Hydrographs located south and east of the wash tray pond show the model is also able to match trends in this area due to changes in recharge at nearby ponds. A few areas particularly in Layer 5 have a poorer match. The hydrograph of simulated heads for well 6D matches the overall increasing trend of the observed data and is similar to hydrographs of observed heads for nearby Layer 5 wells (17D and 34D). However, the hydrograph of observed data in well 6D exhibits a larger increase from early 2004 through mid-2005, followed by a decrease, similar to hydrographs for shallower wells in this area. Well 6D is screened in the upper half of Layer 5, whereas wells 17D and 34D are both screened in the lower half of Layer 5. These data suggest that the upper half of layer 5 is in better communication with the shallower layers than the lower half. It would not be possible to simulate both hydrograph trends without additional vertical discretization.

The mean residual error for the long-term transient calibration was -0.15 feet and the absolute residual mean error was 1.73 feet. **Table 21** presents the calibration statistics for the 82 target locations and 1,369 head targets. The transient simulation provided a good match to both the timing and magnitude of stresses, including the breach in Pond D4. The relatively low absolute residual mean suggest this model is well calibrated to this large-scale long-term transient event.

Table 18. 2004-2005 Transient Model Statistics

Residual Mean (feet)	-0.15
Absolute Residual Mean	1.73
Residual Standard Deviation (feet)	2.17
Range of Observations (feet)	38.8
Standard Deviation/Range of Observations	0.056

Table 22 below shows a comparison of the head statistics by layer. Statistically, the model shows a minor amount of bias between the layers. The absolute residual mean values suggest the match to observed heads in Layer 3 are the best, and the match to Layer 5 heads are the poorest. In addition the residual mean deviates differently from zero for each of the layers. The residual mean statistics suggests that in general; Layer 1 heads are over predicted, Layer 4 heads are under-predicted, and heads in Layer 2, 3 and 5 are relatively balanced between under and over prediction.

Table 22. 2004-2005 Transient Model Statistics by Layer

Layer	Absolute Residual Mean	Residual Mean
Layer 1	1.72	-1.06
Layer 2	1.73	-0.16
Layer 3	0.76	-0.01
Layer 4	1.44	0.76
Layer 5	3.19	0.2

4.2.5 2014 Steady-State Calibration

A total of 49 pumping wells were simulated as actively pumping in the 2014 steady-state model. The pumping rates for these wells were established as the average pumping rate for January 2014. **Table 13** shows the pumping rates used in the 2014 model. Recharge rates used in the 2014 steady-state model are presented in **Figure 63** which ranged from 8.1×10^{-5} to 5.1×10^{-1} feet per day. These rates, as applied over the respective areas, resulted in inflow that was within the range of estimated inflow for background recharge and pond seepage.

Appendix J contains calibration statistics resulting from the 2014 steady-state model based on 165 head targets. All head target statistics, groundwater exchange data, and the other general components of the water balance meet the steady-state model calibration goals. Further, visual comparison of the simulated and observed potentiometric maps show that in general, groundwater flow directions and gradients were similar.

4.2.5.1 2014 Calibration to Head Data

The calculated residual mean for all target wells was 0.27. The industry standard is that this value should be as close to zero as possible (Anderson and Woessner, 1992). The absolute residual mean was 1.76

feet, which meets the calibration goals of less than 2 feet. The residual standard deviation divided by this range was about 2.6% which is less than the calibration goal of less than 10 percent and less than 5 percent for a well calibrated model (Anderson and Woessner, 1992). The maximum residual is 5.23 feet and the minimum residual is -4.5 feet. Only one head target was greater than 5 feet. **Figure 64** is a plot showing observed vs. simulated heads demonstrating that observed and simulated heads are randomly distributed on either side of the regression line indicating the model is well-calibrated (Anderson and Woessner, 1992).

Figures 65 through **70** are maps showing the simulated potentiometric surfaces for Layers 1 through 6, for the 2014 steady-state calibration. Comparison of the computed potentiometric contours to those based on field measurements (**Figures 14** through **17**) indicates a good match between simulated and observed heads and gradients.

Residuals at each target location are shown on **Figures 65** through **69**, with positive (blue) values indicating the simulated head was less than the observed head and negative (red) values indicating the simulated head was greater than the measured value. The residuals posted on these figures allow for a spatial analysis of the calibration. The 2014 simulation over-predicts heads south of the South Cooling Tower Blowdown Pond in Layer 4 (McKay), which might suggest that the model is allowing too much vertical commutation between the McKay and overlying units in this area. The 2014 model also over-predicts heads north of the Sediment Retention Pond in Layer 5, which could suggest is allowing too much vertical commutation between the SubMcKay and overlying units in this area. The 2014 simulation under-predicts heads in and the Townsite area in Layers 3 & 4.

The 2014 simulation under-predicts heads in Layers 1 and 2 alluvial wells west of the Units 1 & 2 A Pond and Sediment Retention Pond in comparison to the 2003 simulation, which generally over-predicted heads in this same area. An effort was made during calibration to both data sets to reduce spatial bias in this area through investigating various combinations of aquifer parameters and pond seepage within reasonable ranges. Results of calibration runs suggested that spatial bias could not be removed from one model without adding more bias to the other. Uncertainty in estimated values of transmissivity, pond seepage, and the simulated pumping rates appeared to be the root cause of this issue. In order to eliminate some of the bias, either seepage from Units 1&2 Pond A and the Sediment Retention Pond had to be higher than estimated in 2014, the aquifer transmissivity had to be higher than estimated, or capture well pumping rates lower than those estimated must be used. Reduction in uncertainty of any or all of these parameters would likely increase the accuracy of the model in this area.

Another way to review the calibration spatially is to review the statistics by layer (**Table 23**). The model shows a minor amount of bias between the layers.

Table 23. 2014 Calibration Statistics by Layer

Layer	Absolute Residual Mean	Residual Mean
Layer 1	1.49	-0.04
Layer 2	1.75	0.84
Layer 3	2.78	1.59
Layer 4	1.51	-0.03
Layer 5	2.07	-0.99

4.2.5.2 2014 Calibration to Flux Data

The components of the 2014 steady-state water balance were compared to the components of the estimated water budget to ensure the model simulation incorporated the appropriate rates of flux. **Table 24** presents estimated groundwater flux values along with corresponding simulated groundwater flux values. All the simulated flux values fall within the estimated ranges. **Appendix J** contains the groundwater model balance resulting from the calibrated 2014 steady-state model.

Table 24. Comparison of Estimated and Simulated Groundwater Flux for 2014

	2013/2014						2014 Steady State Groundwater Model Simulated Water Balance	
	Min (ft^3/d)	Max (ft^3/d)	2013/2014 Estimate (ft^3/d)	Min (gpm)	Max (gpm)	2013/2014 Estimate (gpm)	(ft^3/d)	(gpm)
Inflows								
Underflow In	28,365	113,462	56,731	147	589	295	41,601	216
PPL Pond Seepage	1,830	178,489	18,089	10	927	94	26,377	137
WECO Ponds Seepage	7,567	75,674	23,930	39	393	124	17,754	73
Sewage Lagoons Seepage	16,888	26,738	22,517	88	139	117	24,966	130
Surge Pond Seepage	4,113	41,132	13,007	21	214	68	9,306	48
Recharge (net infiltration)	16,907	28,179	22,543	88	146	117	27,302	142
Outflows								
Underflow Out	27,186	81,559	54,372	141	424	282	49,988	260
Outflow to E.F. Armells Creek	33,209	55,348	44,278	173	288	230	36,680	191
Groundwater Extraction	58,512	86,867	68,643	304	451	357	62,289	324

Table 25 presents the simulated flux from groundwater to East Fork Armells Creek. Unfortunately since no synoptic stream gaging was conducted during this time period (or any other low flow time period), making direct comparisons between the measured and simulated flux to the creek was not appropriate. However, the simulated pattern of flow into East Fork Armells Creek was similar to that observed. The creek loses flow to groundwater between surface water stations AR-5 and AR-4 and significant outflow to the creek occurs downstream of station AR-2.

Table 19. 2014 Simulated Flow from the Groundwater System to East Fork Armells Creek.

	Reach 1 (Domain to AR-5)	Reach 2 (AR-5 to AR-4)	Reach 3 (AR-4 to AR-3)	Reach 4 (AR-3 to AR-2)	Reach 5 (AR-2 to Domain)
Flow to Armells Creek from Groundwater (gpm)	49.6	-8.26	20.9	27.9	100.6

Total estimated groundwater extraction, including flow to underdrains, in January of 2014 was 357 gpm which included 38.5 gpm to underdrains The simulated extraction was slightly lower than this (324 gpm) due to the FWL5 package diminishing flow rates to a few wells and the drains capturing slightly less water than estimated.

4.3 CALIBRATION RESULTS SUMMARY

The Plant Site model is well-calibrated, especially considering the dynamic and complex flow system in the area. Calibration statistics and good visual qualitative matches for the four calibration data sets suggest this model is robust and adaptable to changing hydraulic conditions around the Plant Site.

To clarify, the model developed is one model that has been calibrated to several different time periods. This required creation of variable inputs for certain parameters, such as recharge and pumping rates. However, most parameters incorporated in the model were made consistent for all models including:

- Hydraulic Conductivity Distribution,
- Storage Distribution,
- Conductance values assigned to GHB and River Package cells,
- Model Domain,
- Boundary Locations,
- Grid Spacing, and,
- Layer Elevations,

In consideration of the foregoing, we believe this version of the groundwater model is well-calibrated and can serve as an appropriate tool to conduct predictive exercises, such as groundwater capture analysis, among others.

5.0 SENSITIVITY ANALYSIS

A sensitivity analysis was performed to quantify uncertainty in the calibrated model related to uncertainty in model inputs. The sensitivity analysis helps identify input parameters to which the numerical model is most sensitive. Methods and result of the sensitivity analysis are described below. Additional sensitivity analysis of the model predictions regarding groundwater capture is described in **Section 6.4**.

The sensitivity analysis was conducted using the 2014 steady-state simulation and varying selected values within plausible ranges to document the effect on model calibration statistics. Parameters that appeared to have the greatest effect on residual statistics during manual and automated calibration were selected for selected for analysis, including horizontal and vertical hydraulic conductivity, net infiltration rates, pond seepage rates, conductance of River Package cells simulating East fork Armells Creek, and capture well pumping rates. Horizontal and vertical hydraulic conductivity values in zones selected for analysis included those that comprise a relatively large portion of the model domain, or during calibration were observed to greatly influence model calibration. The horizontal and vertical values were varied separately during the analysis. During calibration it appeared that the model was sensitive to the horizontal hydraulic conductivity of zones representing coarse-grained alluvium. For this reason, the three zones representing coarse-grained alluvium in Layers 2, 3, and 4 were tested as a group during the sensitivity analysis. **Table 26** list model input parameters tested in the sensitivity analysis.

The sensitivity analysis was completed using Groundwater Vistas Auto-Sensitivity function for most parameters. Analysis of a few parameters (e.g. capture well pumping rates) was completed by adjusting values manually due to issues with model convergence, mostly related to the FWL5 package in MODLFOW SURFACT.

The following is a summary of the range of values tested for the different types of input parameters in the sensitivity analysis:

- Horizontal and vertical hydraulic conductivity values were multiplied by 0.1, 0.5, 0.8, 2, 5, and 10;
- Net recharge rates were multiplied by 0.1, 0.5, 0.8, 2, 5, and 10;
- Pond seepage rates were multiplied by 0.1, 0.5, 0.8, 2, 5, and 10;
- River bed conductance was multiplied by 0.1, 0.5, 0.8, 2, 5, and 10;
- Simulated capture wells pumping rates were multiplied by 0.75 and 1.25.

Figures 71 through **75** summarize results of the sensitivity analysis. Results indicate the model calibration is most sensitive to changes in recharge and then to hydraulic conductivity as discussed below.

Table 20. Parameters Altered in the Sensitivity Analysis

Horizontal Hydraulic Conductivity

Zone	Description	Layer
Zone 1	Overburden	1
Zone 2	Fine Grained Alluvium	1
Zone 3	Spoils	1,2
Zone 4	Rosebud Coal	2
Zone 5	Coarse Alluvium	3
Zone 6	McKay Coal	4
Zone 7	Sub-McKay	5
Zone 8	Interburden, small areas fine grained colluvium	2,3
Zone 9	Spoils	1,2,3
Zone 10	Coarse Alluvium	2
Zone 11	Coarse Alluvium	4
Zone 12	McKay Coal	1,4
Zone 13	Fine Grained Alluvium/Colluvium	1,2,3
Zone 14	Fine Grained Alluvium/Colluvium	3,4
Zone 23	Interburden	3
Zone 32	Deep Sub-McKay	6

Horizontal and Vertical Conductivity

Zone	Description	Layer
Zone 5, 10&11	Coarse Alluvium	2,3,4

Vertical Hydraulic Conductivity

Zone	Description	Layer
Zone 2	Fine Grained Alluvium	1
Zone 3	Spoils	1,2
Zone 4	Rosebud Coal	2
Zone 5	Coarse Alluvium	3
Zone 6	McKay Coal	4
Zone 7	Sub-McKay	5
Zone 8	Interburden, small areas fine grained colluvium	2,3
Zone 9	Spoils	1,2,3
Zone 10	Coarse Alluvium	2
Zone 11	Coarse Alluvium	4
Zone 13	Fine Grained Alluvium/Colluvium	1,2,3
Zone 16	Fine Grained Alluvium/Colluvium	3
Zone 23	Interburden	3
Zone 32	Deep Sub-McKay	6
Zone 58	Sub-McKay	5

Pumping

Well	Description
All	Wells were adjusted as a group

Recharge

Zone	Description
Zone 1	Recharge Background
Zone 11	Leakage Cimarron/Townsite Stream
Zone 12	Recharge Clinker Exposures
Zone 16	Recharge Townsite Lawn Areas
Zone 29	Non-paved, Un-vegetated Area of Plant Site

Pond Seepage

Zone	Description
Zone 2	Units 1 & 2 Pond A
Zone 3	Units 1 & 2 Bottom Ash Ponds
Zone 4	South Cooling Tower Blowdown Pond C
Zone 5	WECO Pond PO-10
Zone 6	WECO Sediment Ponds
Zone 7	Units 3 & 4 Bottom Ash Pond
Zone 8	Units 3 & 4 Wash Tray Pond
Zone 9	WECO Pond PO-10A
Zone 10	City of Colstrip Sewer Lagoons
Zone 15	North Cooling Tower Blowdown Pond C
Zone 17	Units 3 & 4 Bottom Ash Pond
Zone 18	Units 3 & 4 Bottom Ash Pond
Zone 19	Units 3 & 4 Bottom Ash Pond
Zone 20	Units 3 & 4 Bottom Ash Pond
Zone 21	Units 3 & 4 Bottom Ash Pond
Zone 22	Units 3 & 4 Bottom Ash Pond
Zone 23	WECO Pond PO-10B
Zone 25	Units 1 & 2 Pond B; Liner at D-4 Brine Pond; Fraction of plant site area
Zone 26	Units 3 & 4 Drain Collection Pond
Zone 27	Former Brine Pond Area D4
Zone 30	Brine Pond Area D1,2, and 3 Pond
Zone 31	Units 1 & 2 Bottom Ash Clear Well
Zone 32	Sediment Retention Pond
Zone 33	Units 3 & 4 Bottom Ash Pond

Riverbed Conductance

Reach	Description
Reach 1	South model boundary to gaging station AR-5
Reach 2	from station AR-5 to AR-4
Reach 3	from station AR-4 to AR-3
Reach 4	from station AR-3 to AR-2
Reach 5	from station AR-2 to the north model boundary

5.1 HYDRAULIC CONDUCTIVITY

Figure 71 presents the results of the sensitivity analysis with respect to hydraulic conductivity. This figure plots the multiplier used in sensitivity runs against the absolute residual mean as an indicator of calibration quality.

The model is most sensitive to small and large increases in vertical hydraulic conductivity of the Deep Sub-McKay (Zone 32, Layer 6). The model is also moderately sensitive to decreases in this parameter in the shallow Sub-McKay (Zone 7, Layer 5) as well as in the deep Sub-McKay. This parameter affects the amount of communication between the shallow local-intermediate flow systems with the deeper regional system. The sensitivity to this parameter indicates the importance of including Layer 6 in the model. Without Layer 6, head in shallow layers would be higher because the model would not take into account water flows down from the shallower units to the regional system.

The model is moderately sensitive to order-of-magnitude decreases in vertical hydraulic conductivity in:

- Interburden in Zone 8 - Layer 3.
- Spoils in Zone 3 - Layers 1 and 2

The model is moderately sensitive to order of magnitude increases in horizontal hydraulic conductivity in:

- Sub-McKay – Zone 7 in Layer 5
- McKay Coal – Zone 6in Layer 4
- Spoils – Zone 3 in Layers 1 and 2

The model is moderately sensitive to order of magnitude decreases in horizontal hydraulic conductivity in:

- Spoils in Zone 3 - Layers 1 and 2

There are a few examples where slight increases (2 to 5 times) in horizontal hydraulic conductivity in alluvium of (zones 2, 5, 10 and 11) actually improved average residuals. However, increases in these zones applied to the 2003 steady-state calibration, the pumping test calibrations and the December 2003-January 2006 transient calibration did not yield similar calibration improvement. In addition, the majority of the coarse-grained alluvium in the model was simulated with values between 70 and 150 feet/day although aquifer test data suggest a few areas may exhibit higher hydraulic conductivity (**Appendix A**). The majority of test results suggested the overall permeability was within the calibrated range.

5.2 NET RECHARGE

Figure 72 presents the results of the sensitivity analysis with respect to net recharge. Results indicate that model is quite sensitive to order of magnitude increases in recharge from:

- Un-vegetated areas of infiltrating recharge (Zone 29),
- Lawn Irrigation (Zone 16), and

- Background net recharge (Zone 1).

The model is much less sensitive to increases in recharge of 2 to 5 times. It is highly unlikely that infiltration thorough unvegetated areas at the Plant Site could be 10 times higher than the calibrated value, which was about 9.5 of the annual precipitation for that year. An order of magnitude increase in recharge would make it equivalent to the annual precipitations. It is plausible that net recharge values for areas of lawn irrigation and background areas could be as much as an order of magnitude higher, but this likelihood is difficult to assess. The model is not sensitive to decrease in net recharge.

5.3 POND SEEPAGE

Figure 73 presents the results of the sensitivity analysis with respect to pond seepage. Results indicate that the model is very sensitive to order of magnitude increases in seepage from:

- Units 3 & 4 Bottom Ash Pond (Zone 7)
- WECO Sediment Ponds (including PO-151), (Zone 6)
- WECO Pond PO-10A (Zone 9)

The model is moderately sensitive to 5 fold increases in these seepage rates. The model is very sensitive to order of magnitude increases in seepage from Units 3 & 4 Bottom Ash Ponds, (Zones 33 and 17). The model is not sensitive to decrease in seepage form the ponds tested.

5.4 RIVERBED CONDUCTANCE

Figure 74 presents the results of the sensitivity analysis with respect to conductance of River Package cells representing East fork Armells Creek. This figure shows that the model calibration is not sensitive to increases or decreases in riverbed conductance.

5.5 PUMPING

Figure 75 presents the results of the sensitivity analysis with respect to pumping rates. This figure shows that the model calibration is somewhat sensitive to both increases and decreases in pumping rates.

5.6 SUMMARY OF SENSITIVITY ANALYSIS RESULTS

The model calibration is most sensitive to large increases in net recharge and pond seepage and large increase in the vertical hydraulic conductivity of the Deep Sub-McKay (Layer 6). The model is moderately sensitive to large increases and decreases in horizontal hydraulic conductivity in some zones and increases or decreases in overall capture pumping rates. Model calibration is insensitive to increases and decreases in riverbed conductance.

6.0 CAPTURE ANALYSIS

Following calibration and sensitivity analyses, the Plant Site numerical groundwater model was used to perform particle tracking simulations to assess the effectiveness of the current groundwater capture system. Particle tracking is used to evaluate both sources of constituents as well as to forecast the fate constituent in areas known to have impacted groundwater. These forecasts should be considered an approximation and additional lines of evidence, such as field measurements of pumping drawdown and trends in water quality, should also be consulted in a weight-of-evidence approach.

Particle tracking simulates advective transport of dissolved constituents in groundwater. Advection is the transport of a solute by the bulk movement of groundwater, the movement of particles within flowing water at the average linear groundwater velocity. Particle tracking does not take into account other hydrodynamic processes that can affect the movement of solutes in groundwater including diffusion, dispersion, retardation (adsorption), or decay (chemical reactions).

6.1 PARTICLE TRACKING SET UP - AREAS EXCEEDING BSLs

MODPATH (Pollack 1994) was used to complete particle tracking simulations to assess the effectiveness of the current groundwater capture system. The program was used to calculate particle pathlines based on advective flow. Head outputs from the 2014 steady-state calibration were used to generate velocity inputs for MODPATH. This simulation included application of January 2014 pumping rates for groundwater capture systems and capture from the underdrains for the Units 1 & 2 Pond B collection and Units 1 & 2 Bottom Ash Pond collection systems. Effective porosity values were assigned to model cells in order to generate velocity inputs for MODPATH. Effective porosity values for different lithologies were estimated based on the ranges presented in **Table 15.** Assigned effective porosity values are summarized in **Table 27** below.

Table 21. Assigned Values of Effective Porosity

Unit	Effective Porosity (unitless)
Fine-grained alluvium	0.15-0.2
Coarse-grained alluvium	0.2
Spoils	0.15
Interburden	0.15
Rosebud Coal / McKay Coal	0.09
Sub-McKay bedrock	0.15

Particles representing non-reactive dissolved constituents were input into areas representing groundwater exhibiting boron, chloride, sulfate concentrations, or field specific conductance concentrations greater than BSLs (**Figures 76** through **80**). Five particle tracking simulations were completed for model Layers 1 through 5. Particle tracking was not completed for Layer 6 because there are no wells screened within this layer and it is not anticipated that any groundwater in the deep Sub-McKay system exceeds BSLs. In each simulation, particles were input into an area that encompassed the known extent of groundwater exceeding BSLs for each layer. These areas were delineated as follows:

- Layer 1 – The extent in this layer (**Figure 76)** was delineated using all the plume maps for alluvium and spoils (**Figures 21** through **28**) and any BSL exceedance measured in an overburden well.
- Layer 2 – The extent in this layer (**Figure 77)** was delineated using all the plume maps for alluvium and spoils (**Figures 21** through **28**) and any BSL exceedance in a Rosebud well.
- Layer 3 – The extent in this layer (**Figure 78)** was delineated using all the plume maps for alluvium (**Figures 21** through **24**) and any BSL exceedance in an interburden well. Due to the scarcity of wells screened in interburden, the assumption was made that areas with exceedances in the underlying McKay Coal also would have exceedances in that area in the overlying interburden.
- Layer 4 – The extent presented in this layer (**Figure 79**) was delineated using all the plume maps for alluvium (**Figures 21** through **24**) and any BSL exceedance in a McKay well.
- Layer 5 – The extent in this layer (**Figure 80**) was delineated using any BSL exceedance in a Sub-McKay well.

A few isolated wells sampled in early 2014 (Wells 103D, 99D, 28SP, 63S, 36M, WM-125) exceeded the chloride BSL, but generally did not exceed BSLs for other constituents of concern. These wells are isolated from other wells that appear to be impacted by process ponds and are all located adjacent to roads. It is anticipated that the source of chloride detected in these wells is not process ponds and may be attributable to magnesium chloride used for dust suppression. Because of this, areas surrounding these wells were not included in the areas depicted in **Figures 76** through **80** and were not used as starting locations for the particle tracking analysis.

A single particle was placed in every saturated model cell within Layers 1 through 5, in the areas shown in **Figures 76** through **80**, respectively. Particle starting locations were set to the vertical center of the model cell except for in Layers 1 and 5. The vertical starting location in Layer 1 was set to the cell bottom to ensure the particle was placed in a saturated location. Layer 5 is 75 to 135 feet thick and most of the wells in this layer that exceed BSLs only partially penetrate the area. For this reason, particles in Layer 5 were placed at the top of the cell. Forward particle tracking for each simulation was then executed, and the particles were moved through the steady-state flow field over 50-year and 500-year periods.

6.2 CAPTURE ANALYSIS RESULTS –AREAS EXCEEDING BSLS

Electronic versions of Figures 81 through **85** present animated tracks for particles started in each layer as they move through the 50-year simulation. Printed versions of these figures will show only horizontal positions of the particle tracks. As the particles move into other layers they are symbolized with a different color.

Particles originating in alluvium in Layer 1 (**Figure 81**) on the western side of the Plant Site generally migrate to the northwest and are mostly captured by alluvial pumping wells along the western margin of the Plant Site. Many of these particle move downward into the Sub-McKay as a result of downward gradient caused by lower head in this unit before being captured generally by deep alluvial or Sub-McKay wells. Particles initiated on the west side of East Fork Armells Creek near well OT-7 and the City of Colstrip Sewage Lagoons migrate east-northeast terminating in River Package cells simulating East Fork Armells Creek. Particle tracking results indicate that many of the particles started in the Units 3 and 4

Bottom Ash Pond area escape to the east. Particles started around the Units 3 & 4 Wash Tray Pond do not travel far laterally in the 50-year simulation. Some particles started around D-1 through D-4 Brine Ponds travel to the northwest toward capture systems other particles travel toward capture wells within the Brine Pond area.

Particles released in coarse-grained alluvium, Rosebud Coal, and spoils, Layer 2 (**Figure 82**) generally follow similar pathways and are captured by a similar set of wells as particles released in Layer 1. Particles started on the west side of East Fork Armells Creek near well OT 7 and the Sewage Lagoons end at East Fork Armells Creek. Particle tracking results indicate that many of the particles started in the Units 3 & 4 Bottom Ash Pond area are transported to the east and are not captured within the 50-year simulation. Particles started around the Units 3 & 4 Wash Tray Pond generally travel downward and do not travel far laterally in the 50-year simulation. Particles started in Layer 2 around the D-1 through D-4 Brine Ponds tend to travel down into Layer 3 (interburden) some particles travel toward capture wells within the Brine Pond area.

Particles released in interburden and coarse-grained alluvium in Layer 3 (**Figure 83**) on the western side of the Plant Site generally move northwest and are captured by pumping wells. Particles started on the west side of East Fork Armells Creek near well OT 7 and the Sewage Lagoons travel to the East Fork Armells Creek. A few particles released near the North Plant Area Drain Pond in Layer 3 are transported west to East Fork Armells Creek without being captured. A few particles started in Layer 3 near Brine Ponds D-1 through D-4 and around the Units 3 & 4 Wash Tray Pond do not travel far laterally in the 50 year simulation.

Particles released in McKay Coal and coarse-grained alluvium in Layer 4 (**Figure 84**) on the western side of the Plant Site generally move northwest and are captured by pumping wells. Particles started on the west side of East Fork Armells Creek near well OT-7 and the Sewage Lagoons travel to the East Fork Armells Creek. A few particles released near the North Plant Area Drain Pond are not captured by extraction wells but, rather, are transported to East Fork Armells Creek. Particles started around the D-1 through D-4 Brine Ponds and around the Units 3 & 4 Wash Tray Pond do not travel far laterally in the 50-year simulation.

Particles released in Sub-McKay bedrock (Layer 5) west of the Units 1 & 2 Pond A (**Figure 85**) move northwest toward capture wells. All of these particles are captured within the 50-year simulation.

The electronic versions of **Figures 81** through **85** all show the effect of the downward gradients forcing particles into deeper units except near wells where extraction reverses the vertical gradient.

6.2.1 Analysis of Captured and Uncaptured Particles

In a few areas, particles were still moving through the groundwater system after 50 years. To evaluate whether these particles would eventually migrate beyond the capture system, the capture analysis simulations were extended to 500 years, and an end-point analysis was performed to predict the ultimate fate of these particles. **Table 28** summarizes results of the end-point analysis.

Table 22. Summary of Uncaptured Particle

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Total
Total Particles	10,498	16,521	12,403	11,437	2,165	53,024
Particles Uncaptured after 50 years	2,029	2,576	1,661	1,741	0	8,007
Particles Never Captured (after 500 years)	174	151	71	79	0	475

The end-point analysis indicates the vast majority of the over 53,000 particles simulated would be captured eventually. However, many particles in Layers 1 through 4 are not captured within 50 years and some particles are never captured. All particles initiated in Layer 5 were eventually captured. Of the 475 (0.9 percent of the total particles) uncaptured particles initiated in the upper four layers, 238 (0.45 percent of the total particles) eventually enter East Fork Armells Creek. The uncaptured particles that enter East Fork Armells Creek entered the creek in the area just south of the City of Colstrip Sewage Lagoons (near stream gage AR-3). It is understood that this area is a gaining stretch of the river as evident by the synoptic stream flow measurements (see Figure 9). The model has simulated this area of East Fork Armells Creek as a gaining reach. The remaining 237 particles travel to the eastern model boundary.

The starting locations of all uncaptured particles determined by the end point analysis was then identified. **Figures 86** through **89** present the starting locations in Layer 1 through 4 for uncaptured particles. These figures show possible locations of source areas generating potentially impacted groundwater that are not being captured by the current (January 2014) capture system. The following summarizes the source areas for uncaptured particles.

- Particles started on the west side of East Fork Armells Creek near well OT-7 and the Sewage Lagoons are not captured by extraction wells, but they are transported to East Fork Armells Creek.
- A few particles started in the interburden and McKay (Layers 3 & 4) near the North Plant Area Drain Pond are not captured by extraction wells, rather these particles are eventually transported to East Fork Armells Creek.
- Many particles released on the east side of the 3 & 4 Bottom Ash Ponds are transported to the east-southeast toward the Cow Creek draining and are not captured.
- A few particles west of, and in the center of, the 3 & 4 Bottom Ash Ponds are not captured. These particles migrate downward along vertical gradients and eventually become entrained in the deep regional flow system and are transported to the northeast.
- Similarly, a few particles along the southern end of the Units 3 & 4 Cooling Tower Blowdown Pond are not captured. The model indicates the particles slowly migrate downward and eventually (generally after more than 100 years) would enter the deep regional flow system and be transported to the northeast.

6.2.2 Summary of Capture Analysis- Areas Exceeding BSLs

This analysis suggests that groundwater exceeding BSLs for indicator parameters originating from most known source areas in the Plant Site area will be intercepted by the capture system. Capture analysis results also suggest that the current capture system may not be completely capturing groundwater originating from the following areas:

- Areas of BSL exceedance in the alluvial groundwater around OT-7 and the Sewage Lagoons,
- A small area of BSL exceedance in the interburden and McKay around the North Plant Area Drain Pond,
- Areas of exceedance in spoils around the Units 3 & 4 Bottom Ash Ponds, and
- An area of BSL exceedance in spoils, Rosebud, interburden and McKay near the southern end of the Units 3 & 4 Cooling Tower Blowdown Pond.

This analysis was based on the 2014 steady-state model, which represents conditions from the first quarter of 2014. Since this is a steady-state model, short-term transient effects were not simulated. Seasonal effects, such as increase in the stream stage, changes in pond management, and changes in number or pumping rates of capture wells, may slightly alter simulated particle traces. Since travel times in most units are relatively long (months to years), a steady-state analysis should represent groundwater capture adequately. The one area where transient stresses could have an effect on predicted capture is in coarse-grained alluvium along East Fork Armells Creek west and north of the Plant where velocities are faster and travel distance to a receptor, the creek, is shorter.

As noted above, particle tracking does not take into account processes of attenuation (dispersion, retardation, decay) and is not capable of quantifying mass or concentrations of solutes in the aquifer or mass of solutes removed by capture systems.

6.3 CA-19 AND OT-7 AREA CAPTURE ANALYSIS

Reverse particle tracking was performed in an effort to identify possible source areas for groundwater exceeding BSLs near well OT-7, and formerly exceeding BSLs at CA-19. As described above, evidence suggests that process ponds are not the source of elevated levels of indicator parameters detected in these wells. Particles were placed in a circle immediately surrounding each of these wells and moved backwards through the flow field for 50 years. Results of reverse particle tracking are show in plan view in **Figure 90** and in cross-sectional view in **Figure 91**. Results of reverse particle tracking for well CA-19 indicate that water sampled from the well originates at the water table a very short distance southwest of the well, not from the Plant Site. Particle tracking for well OT-7 indicates some of the water sampled from OT-7 originates from East Fork Armells Creek, and some originates from the west, beneath the Colstrip Townsite.

6.4 CAPTURE ANALYSIS UNCERTAINTY

Uncertainty associated with some model inputs creates uncertainty in model predictions such as the capture analysis described above. An uncertainty analysis was completed to evaluate how sensitive capture analysis results are to input parameters that are anticipated to have both a relatively high degree of uncertainty and also impact predicted capture results. Parameters evaluated were those judged to have the greatest effect on capture analysis results, including pumping rates and effective porosity.

6.4.1 Capture Analysis Uncertainty-Pumping Rates

As described above, there is uncertainty associated with pumping rates in Plant Site capture wells due to the difficulty in measuring flow rates at individual wells. Model calibration and sensitivity analyses indicate that the model is sensitive to changes in pumping rates in capture wells located near Units 1 and 2 Pond A. Sensitivity analysis indicates that realistic transmissivity values assigned to the alluvial system would not support the 2014 estimated pumping rates without creating more drawdown than is suggested by groundwater elevations measured in wells in this area. Hydrometrics personnel indicate that scaling within the plumbing associated with the systems and obtaining accurate flow measurements from the systems are problems in capture wells located along the west side of A Pond. Because of this, these west side capture wells, in particular, may be the main source of uncertainty associated with Plant Site capture rates.

Two additional capture analyses were performed to help further evaluate the uncertainty described above as related to capture well pumping rates:

- Sensitivity analysis suggested the model is moderately sensitive to changes in capture rates of ± 25 percent. Extraction rates used in the 2014 calibration were multiplied by 0.75. Particles were initiated at the same starting locations as described in **Section 6.1**. Forward particle tracking was then executed, and the particles were moved through the steady-state flow field.

- Assuming it is possible that actual pumping rates in west side capture wells could be much lower than estimated, extraction rates in wells west of Units 1 and 2 Pond A (wells SRP1 through SRP-8, 31M, 122A, 117A, 108A, 107A, 106A, 118A, 116M, 10S, 10M, 5M, 115M, 58M, 98M, 59M, 114S, 1D, 58D, 56D) were multiplied by a factor of 0.5, the remaining wells were simulated to pump at the same rates used in the 2014 calibration. The same particle starting locations as described in **Section 6.1** were released into the model. Forward particle tracking was then executed, and the particles were moved through the steady-state flow field.

6.4.1.1 All Extraction Rates Multiplied by a Factor of 0.75

Particle tracking results were largely similar to those described in **Section 6.2** above. **Table 29** summarizes results of capture analysis under this scenario indicating that most particles released in Layers 1 through 4 were captured and all particles released in Layer 5 were captured. **Table 28** indicates that a total of 852 particles (1.6 percent of the total particles) were uncaptured, and of these, 423 (0.8 percent of the total) entered East Fork Armells Creek. This is an increase of 185 particles entering East Fork Armells Creek (from 238 to 423) relative to the analysis with the calibrated model.

Table 23. Summary of Uncaptured Particles with Extraction Rates Reduced by a Factor of 0.75

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Total
Total Particles	10,498	16,521	12,403	11,437	2,165	53,024
Particles Uncaptured after 50 years	2,068	2,441	1,568	1,935	0	8,012
Particles Never Captured (after 500 years)	310	271	125	146	0	852

Starting locations for uncaptured particles in Layer 1 through 4 were determined and are shown on **Figure 92**. These figures show possible source areas that are not being captured, which are very similar to the locations described above.

6.4.1.2 Extraction Rates Exclusively at Wells West of Pond A Reduced by a Factor of 0.5

With this analysis, a very similar flow field and similar particle traces developed for all areas except near Units 1 and 2 Pond A. In this scenario, more particles escape capture and were transported to East Fork Armells Creek. A total of 327 particles entered East Fork Armells Creek. This is an increase of 89 particles entering the creek (from 238 to 327). Although the pumping rate change adjacent to Pond A was large in this analysis, other wells, including the high-yield well 79A, continued to pump at the originally assigned rates. This is likely why the increase in the number of particles entering the creek was smaller in this uncertainty scenario.

6.4.1.3 Summary of Capture Analysis Uncertainty-Pumping Rates

The uncertainty in the capture analysis with regarding to pumping rates suggest that, although there is uncertainty in the measured pumping rates at the Plant Site, altering this parameter does not dramatically alter the prediction of capture performance.

6.4.2 Capture Analysis Uncertainty – Effective Porosity

Time-of-travel predictions are sensitive to effective porosity because groundwater velocity is inversely proportional to effective porosity. Travel time is based on interstitial velocity (flow limited to aquifer pores) not Darcy velocity (flow across a full cross-section of aquifer). Effective porosity is difficult to measure in the field and site-specific data were not available. As discussed in **Section 3.0** and **4.0,** the model was populated with conservative literature-derived values for effective porosity. Since this parameter has high uncertainty, particle tracking was performed to assess the implications to capture from varying this input.

Since effective porosity does not alter the flow field in any way, the same particles would be captured and uncaptured with this analysis as presented in **Section 6.2**. However, effective porosity does impact the time-of-travel. With this in mind, the model was populated with a sparse set of particles, starting at locations that fell within the areas of BSL exceedance (presented in **Section 6.1**). The sparse set of particles allowed for visualization of the travel time along the particle trace. This analysis was also completed for a reduced period of time (10 years). Two additional simulations were designed and executed: a "low" effective porosity simulation and a "high" effective porosity simulation. For the low and high effective porosity scenarios, effective porosity was set to low and high values respectively, according to the range in literature (**Table 15**). **Table 30** below presents the effective porosity assigned to each zone in the model for these two scenarios, along with the values assigned in the standard case (presented in **Section 6.2**).

Figure 93 presents the results of this analysis. The most notable difference between the scenarios is that, under the low-end effective porosity scenario the seepage velocities are high enough that particles that originated from the Cooling Tower Blowdown Pond and Units 3 and 4 Wash Tray areas were captured within 10 years whereas with the standard and high effective porosity scenarios, the seepage velocities were low enough that the particles did not travel far enough to be captured.

Table 30. Effective Porosity Values Applied to Uncertainty Simulations

Material	Zone	Low Effective Porosity Scenario	Standard Effective Porosity	High Effective Porosity Scenario
Sand and gravel	6,8,9,10	0.2	0.2	0.35
Silt	5	0.01	0.15	0.3
Siltstone	4	0.01	0.15	0.35
Coal	2	0.008	0.09	0.094
Spoils	3 and 7	0.138	0.15	0.164
Sandstone and siltstone	1	0.01	0.15	0.4

7.0 MODEL ASSUMPTIONS AND LIMITATIONS

The numerical model described herein is capable of simulating groundwater flow within the area of interest under a variety of conditions within a reasonable range. The model is appropriate for assessing the effects of changes in water management practices at the Plant Site on groundwater flow and advective transport. It should be noted that because particle tracking (an advective transport analysis) does not take into account processes of attenuation (dispersion, retardation, and decay), it is not capable of quantifying mass or concentrations of solutes in the aquifer or mass of solutes removed by capture systems.

Groundwater models are mathematical representations of groundwater systems and therefore include assumptions and limitations. There are certain inherent assumptions in the use of MODFLOW to simulate groundwater flow including:

- Saturated-flow conditions exist throughout the model domain;
- Darcy's Law applies;
- The density of ground water is constant; and
- The principal directions of horizontal hydraulic conductivity or transmissivity do not vary within the system, aquifer heterogeneity and anisotropy can be adequately represented with an appropriate choice of aquifer properties and grid spacing.

The model includes other important assumptions:

- Specific equipotential contour lines used to assign GHBs and no-flow boundaries provide an accurate and reasonable representation of the flow field at model boundaries.
- Steady-state boundary conditions, based on average pumping and recharge rates, result in representative flow fields. This assumes that transient aquifer stresses that are not simulated would not produce significantly different results.
- Estimated capture well pumping rates are representative of actual rates.
- Flow in fractured bedrock can be approximated as an equivalent porous medium.
- Vertical discretization within the model is fine enough to capture the depth-specific flow fields.
- The range of aquifer properties estimated from field-based data provides a reasonable range of site values.
- Any unknown water management practices of Western Energy (i.e., possible groundwater abstraction or land application of water) do not significantly impact the groundwater system around the Plant Site and Colstrip Townsite.

There is a degree of uncertainty inherent in any model and its application. In this case, there is uncertainty associated with model inputs such as pond seepage rates, pumping rates, areal recharge, and hydraulic properties. The model includes an underlying assumption that the aquifer inhomogeneity and anisotropy can be adequately characterized with an appropriate choice of aquifer properties and grid size. Sedimentary processes that formed interfingered sandstone, shale, mudstone and coal strata in the Fort Union Formation likely created changes in vertical and horizontal hydraulic properties on the scale of tens of feet or less. In addition, the model assumes that flow in bedrock units is horizontally isotropic and therefore it does not simulate any undocumented preferential flow paths that could be present. The process of strip-mining and backfilling of pits with spoils also creates a heterogeneous distribution of materials at many scales which, along with layering and interfingering of alluvial and colluvial units results in heterogeneity at tens of feet or less.

The ability of the model to accurately predict changes in groundwater flow and advective transport at the scale of tens of feet or less may be limited, especially in areas with complex flow characteristics. For these reasons, model predictions should not be viewed as certainties but as the best interpretation of likely outcomes based on available information and data. Additional lines of evidence, such as field-measurements of drawdown and trends in water quality, should be consulted along with the model predictions to evaluate capture system performance.

8.0 CONCLUSIONS AND RECOMMENDATIONS

Calibration of the numerical groundwater flow model described in this report demonstrates the model is capable of simulating groundwater flow and advective transport under a variety of hydrogeologic conditions. The numerical model is appropriate for use in evaluating elements of the conceptual model and the efficacy of groundwater capture systems, either currently operating or being considered in the future.

Development of the conceptual and numerical groundwater flow model, along with model calibration, model sensitivity analysis, and capture analysis, have led to the following conclusions:

- The Plant Site area has a complex and dynamic groundwater flow system. In addition to complex hydrostratigraphy and diverging groundwater flow, several impoundments provide sources of variable seepage to groundwater. These include the Plant Site process ponds, WECO sediment ponds, the Surge Pond, and the City of Colstrip Sewage Lagoons. Periodic dewatering of nearby strip-mines has also influenced groundwater flow.
- Groundwater quality that has been influenced by seepage from current and former process ponds at the Plant Site is characterized by elevated levels of certain parameters, including dissolved boron, chloride, SC, and TDS.
- A few areas peripheral to the Plant Site exceed the chloride BSL, but generally do not exceed BSLs for other constituents of interest. Sources other than process ponds may be responsible for chloride detected in these areas.
- Increased pumping of the groundwater capture system over the last 10 years has changed gaining reaches of East Fork Armells Creek near the Plant Site into losing reaches.
- Groundwater capture via drains and wells is the largest component of outflow for the groundwater budget.
- Vertical gradients are mostly downward within the Site, except near gaining reaches of East Fork Armells Creek and due to pumping around some capture wells finished in shallower units (e.g. spoils, overburden and alluvium).
- The numerical groundwater flow model has been calibrated to multiple sets of hydrogeologic data that represent a range of conditions and is able to reproduce flow fields, heads, and fluxes within a reasonable range of error under a variety of hydrologic stresses. This provides confidence in the predictive capabilities of the model.
- The numerical groundwater flow model is most sensitive to recharge rates, particularly recharge through unvegetated portions of the Plant Site and seepage from the Units 3 & 4 Bottom Ash Ponds and WECO Sediment Pond PO-151.
- Capture analysis of the areas exceeding BSLs suggests that the vast majority of groundwater exceeding BSLs is captured (at least 98 percent of particles were captured) by the current capture system (exceptions noted below).
- Capture analysis indicates that groundwater in two areas that currently exceed BSLs would flow into East Fork Armells Creek without being captured by the current system:

  - Particles in alluvial groundwater near well OT-7 and the Sewage Lagoons is predicted to reach the creek in few years, and,
  - Particles in a small area of groundwater in the interburden and McKay around the North Plant Area Drain Pond is predicted to reach the creek after more than 50 years.
- Capture analysis indicates some areas of groundwater exceeding BSLs would remain within the Plant Site area but would not be captured using the current system within 50 years including:
  - An area in spoils and bedrock under the Wash Tray Pond,
  - Areas around the former Brine Ponds,
  - Groundwater in Rosebud, interburden and McKay hydrostratigraphic units from beneath the South Units 3 & 4 Cooling Tower Blowdown Pond.
- The model predicts other areas would never be captured using the current system including:
  - Groundwater in spoils around the 3 & 4 Bottom Ash Ponds,
  - Groundwater in spoils, Rosebud, interburden and McKay hydrostratigraphic units south of the South Units 3 & 4 Cooling Tower Blowdown Pond.
- Results of reverse particle tracking analyses completed for well CA-19 indicate that water sampled from the well originates at the water table a short distance southwest of the well, not from the Plant Site. Reverse particle tracking analyses completed for well OT-7 indicates some of the water sampled from OT-7 originates from East Fork Armells Creek and some originates from the west, beneath the Colstrip Townsite.
- Predictive uncertainty analysis shows that the portion of captured vs. uncaptured particles does not vary substantially with reduction in groundwater capture rates. This analysis suggests that the current groundwater capture analysis is not very sensitive to decreases in capture well pumping rates.
- Based on the fact that the modeled total pumping rate is the largest component of outflow in the groundwater budget and that simulating capture with reduced pumping rates achieved nearly full capture, the capture system could be optimized to achieve more efficient capture.

In developing the conceptual and numerical models, several potential data gaps have been identified and are discussed briefly below.

- Even though, simulation of plume capture using particle tracking was not sensitive to adjustment of current capture rates, future capture analysis that might consider fewer active pumping wells and/or lower pumping rates might be sensitive to this parameter. Developing a more accurate method of measuring capture well pumping rates would increase model accuracy.
- The water balance and flux targets for the steady-state models are currently based on synoptic stream flow measurements obtained during spring-time conditions. Completing a synoptic gaging run during dry /low water season (October- March) would help increase model accuracy and enhance the understanding of groundwater/surface water interactions.

- Particle tracking suggests that groundwater originating from the Units 3 and 4 Bottom Ash ponds is moving to the east. There are currently no monitoring wells in this area. Installation of monitoring wells would better define groundwater flow and quality in this area.
- The groundwater model extends over a relatively large region. Currently, water level data used in the model to establish boundaries and head targets were derived from various time periods. A groundwater level measurement event conducted during a single monitoring event (during low water season (October-March) would be best) including Plant Site wells, Colstrip Townsite wells, Western Energy wells, and Surge Pond wells would provide for a better calibration data set and better justification of model boundaries.
- Currently, the surface water elevations in several WECO sediment ponds (particularly PO-151, PO-10A, and PO-10B) are unknown. Surveying elevations of water surfaces at these locations would enhance the understanding of groundwater/surface water interaction and the importance of these ponds as potential sources of recharge to the groundwater system.
- Water quality analyses suggest some abandoned pond areas that periodically fill with water and ultimately recharge the local groundwater system may be source areas for constituents of interest. These include the Units 3 & 4 Wash Tray Pond and the former Brine Ponds. Currently, only limited data exist regarding the timing of filling of these ponds and the duration of ponded water in the impoundments. If PPLM elects to maintain the depressions of the former ponds, monitoring water conditions in these impoundments would allow more accurate estimation of groundwater recharge.

Based on these conclusions NewFields recommends that monitoring wells be installed in the following areas:

- <u>East of the Units 3 & 4 Bottom Ash Ponds</u>: Particle tracking indicates that there could be groundwater originating from the Bottom Ash ponds that is migrating east and south east of this area. Installation of monitoring wells in areas marked A and B on **Figure 94** would provide data to help evaluate if groundwater exceeding BSLs is present in this area and migrating east of the Plant Site.

- <u>South of the South Cooling Tower Blowdown Pond C:</u> The conceptual model indicates that groundwater south of this area may be flowing south toward mine cuts in Rosebud Mine Area B, and that groundwater levels in this area have been affected by changes in water management. Installation of monitoring wells in the area marked C on **Figure 94** will help identify the influence of WECO Pond PO-10B on groundwater flow directions in this area. Installation of a monitoring well in the area marked D on **Figure 94** would help verify groundwater flow directions in the area between the South Cooling Tower Blowdown Pond C and Area B and confirm that impacted groundwater is not migrating south of this area.

- <u>West of the North Plant Area Drain Pond:</u> Particle tracking indicates that there could be groundwater originating from the North Plant Area Drain Pond that is migrating west toward East Forks of Armells Creek and not being captured. Installation of a monitoring well or wells in the area marked E on **Figure 94** would confirm or deny whether impacted water is migrating westward from this area. If there is saturated unconsolidated material at location E, NewFields recommends two wells be completed here. One well should be screened across the water table to the bottom of the unconsolidated material. The second well should be drilled 20 feet into bedrock (likely Sub-McKay) and constructed with a 15-foot well screen. If unconsolidated material is unsaturated at this location, only the bedrock well completion is recommended.

9.0 REFERENCES

AMEC Geomatrix. 2009. Proposed Work Plan, 2009 Plant Site Groundwater Modeling, Colstrip Steam Electric Station, Colstrip, Montana. Prepared for PPL Montana LLC. March.

Anderson, M.P. and W.W. Woessner. 1992. Applied Groundwater Modeling, Simulation of Flow and Advective Transport. Academic Press, Inc.

ARCADIS. 2007. Data Analysis and Statistical Evaluation of Unimpacted Groundwater Quality. May.

Bechtel. 1982. Investigation and Control of Seepage at the Surge Pond Dam. April

Bouwer, H. 1982. Design Considerations for Earth Linings for Seepage Control. Groundwater, Vol. 20, No. 5. September-October 1982.

Brown, R.L. and R. R. Parizek. 1971. Shallow Ground Water Flow Systems beneath Strip and Deep Coal Mines Two Sites, Clearfields County Pennsylvania. The Pennsylvania State University, University Park, Special Report of Research SR-84. 207pp

Burton, D. and L.J. Wood. 2013. Geologically-based permeability anisotropy estimates for tidally-influenced reservoirs using quantitative shale data. Petroleum Geosciences. Vol. 19. P. 3-20

City of Colstrip 2014. City of Colstrip's Official Web Site. **http://cityofcolstrip.com/index.php?option=com_content&view=article&id=95&Itemid=502**.

Collier, C.R. 1964 Influences of Strip Mining on the Hydrologic Environment Parts of Beaver Creek Basin, Kentucky, 1955-59. Geological Survey Professional Paper 427-B. U.S. Department of the Interior.

Cosan, A., N. Colley, G. Cowan, E. Ezekwe, M. Wannell, P. Goode, F. Halford, J. Joseph, A Mongini, G. Obondoko, J. Pop. 1994. Measuring Permeability Anisotropy: The Latest Approach. Oil Field Review. October.

Domenico, P.A. and F.W. Schwartz. 1990. Physical and Chemical Hydrogeology. John Wiley & Sons, Inc., New York, NY.

Doherty, J. 2005. PEST Model-Independent Parameter Estimation User's Manual: 5th Edition. Watermark Numerical Computing.

Driscoll, F.G. 1991. Groundwater and Wells. Johnson Division. 1089pp.

Fetter C.W. 1994. Applied Hydrogeology 3rd Edition. Macmillan College Publishing Company, New York.

Flores, R.M. and F.G. Ethridge. l985. Evolution of intermontane fluvial systems of Tertiary Powder River Basin, Montana and Wyoming, in Flores, R.M., and Kaplan, S.S., eds., Cenozoic Paleogeography of the West-Central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Symposium 3, p. l07-l26.

Flores, R.M., A.M. Ochs, L.R. Bader, R.C. Johnson, and D. Vogler. 1999. Framework Geology of the Fort Union Coal in The Powder River Basin. U.S. Geological Survey Professional Paper 1625-A.

Geomatrix. 2006. Plant Site Area Groundwater Model Development and Calibration, Colstrip Steam Electric Station, Colstrip, Montana. Prepared for PPL Montana. February.

Geomatrix. 2007. Conceptual Model Update Report, Stage I and II Evaporation Ponds and Plant Site Areas, Colstrip Steam Electric Station Colstrip, Montana. Prepared for PPL Montana. July 2007

Geomatrix. 2008. Groundwater Modeling Update Report, Plant Site Area, Colstrip Steam Electric Station, Colstrip, Montana. Prepared for PPL Montana. May 2008.

GWIC. 2014. **http://mbmggwic.mtech.edu/**

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald. 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model – user guide to modularization concepts and the ground-water flow process. U.S. Geological Survey Open-File Report 00-92.

Hawkins, J.W. 1995. Impacts on Ground-water Hydrology from Surface Coal Mining in Northern Appalachia. International Mine Water Association. Water Resources at Risk May 14-18 1995 Denver Co. American Institute of Hydrology.

Hayes P.T. 1975 Cambrian and Ordovician Rocks of Southern Arizona and New Mexico and Westernmost Texas. Geological Survey Professional Paper 873.

Holzwarth, M. 2008. Personal Communication. Plant site Operations Manager, PPL Colstrip Steam Electric Station. Telephone conversation with A. C. Stringer and A. Tallman Geomatrix Consultants, Inc. February 11, 2008.

HydroGeoLogic. 1998. MODFLOW-SURFACT v. 3.0: A comprehensive MODFLOW-based flow and transport simulator. Code Documentation Report. HydroGeoLogic, Reston, VA.

Hydrometrics. 1995. Investigation of the Quality of Groundwater and Surface Water in the Colstrip Plant Site and 1 & 2 Evaporation Pond Areas. Prepared for Montana Power Company. January.

Hydrometrics. 2001. Technical Memorandum to PPL Montana. 2000 East Fork Armells Creek. January, 2001.

Hydrometrics. 2007. PPL Montana Plant Site 2004, 2005, 2006 Update Report. Prepared for PPL Montana. August 2007.

Hydrometrics. 2010. Technical Memorandum to PPL Montana. 2010 East Fork Armells Creek Synoptic Run and Groundwater Sampling. July 6, 2010.

Hydrometrics. 2011. Evaluation of 2010 Hydrologic Monitoring Data from Colstrip Units 1 through 4 Process Pond System, Colstrip Steam electric Station, Colstrip Montana. April

Hydrometrics. 2010. PPL Montana, LLC East Fork Armells Creek 2010 Synoptic Run. July. Hydrometrics 2012 Evaluation of 2011 Hydrologic Monitoring Data from Colstrip Units 1 through 4 Process Pond System, Colstrip Steam Electric Station Colstrip, Montana. June.

Hydrometrics. 2012a. Technical Memorandum to PPL Montana. 2012 East Fork Armells Creek Synoptic Run and Groundwater Sampling. November 8, 2012.

Hydrometrics. 2012b. Evaluation of 2011 Hydrologic Monitoring Data from Colstrip Units 1 through 4 Process Pond System, Colstrip Steam Electric Station Colstrip, Montana. June

Hydrometrics. 2013a. Evaluation of 2012 Hydrologic Monitoring Data from Colstrip Units 1 through 4 Process Pond System, Colstrip Steam Electric Station Colstrip, Montana. June.

Hydrometrics, 2013b. Former D4 Brine Pond GeoProbe Investigation. PPL Montana, LLC, Colstrip Steam Electric Station. July.

Hydrometrics. 2014a. Technical Memorandum to PPL Montana. 2014 East Fork Armells Creek Synoptic Run and Groundwater Sampling. July 19.

Hydrometrics. 2014b. Evaluation of 2013 Hydrologic Monitoring Data from Colstrip Units 1 through 4 Process Pond System, Colstrip Steam Electric Station Colstrip, Montana. April.

Hydrometrics, 2015. PPL Montana, LLC. Colstrip Steam Electric Station Administrative Order on Consent Plant Site Report. Updated January.

Lovanh, N., Zhang, Y-K, Heathcote, R.C., Alvarez, P.J.J., 2000. Guidelines to Determine Site Specific Parameters for Modeling Fate and Transport of Monoaromatic Hydrocarbons in Groundwater. Submitted to Iowa Comprehensive Petroleum Underground Storage Tank Fund Board, from The University of Iowa, Iowa Institute of Hydraulic Research, and Iowa Department of Justice. October 2000.

Maxim. 2004. Preliminary Conceptual Hydrogeologic Model Stage I and II Evaporation Ponds and Plant Site Areas. Prepared for PPL Montana. July 2004.

MDEQ. 2012. Administrative Order on Consent Regarding Impacts Related to Wastewater Facilities Comprising the Closed-Loop System at Colstrip Steam Electric Station, Colstrip Montana. Montana Department of Environmental Quality, July 2012.

Morris D. A. and A.I. Johnson. 1967 Summary of Hydrologic and Physical Properties of Rock and Soil Materials, as Analyzed by the Hydrologic Laboratory of the U.S. Geological Survey, 1948-60. Water Supply Paper 1839-D

Nichols, D.J., J.A. Wolfe, and D.T. Pocknall. 1989. Late Cretaceous and early Tertiary history of vegetation in the Powder River Basin, Montana and Wyoming: 28th International Geological Congress, Field Trip Guidebook T132, p. T132:28- T132:33.

Nicklin Earth and Water 2014. Appendix L Area B Permit C1984003B Comprehensive Evaluation of Probable Hydrologic Consequences Areas A,B,C Western Energy Rosebud Mine. Prepared for Western Energy Company. January 2014.

Pollock, D.W. 1994. User's guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post processing package for MODFLOW, the U.S. Geological Survey finite difference groundwater flow model. Reston, Virginia, U.S. Geological Survey.

PPL Montana (PPLM). 2001. Evaluation of 2000 Hydrologic Monitoring Data from the PPL Montana, LLC Process Pond System at Colstrip, Montana.

PPL Montana (PPLM). 2006. Evaluation of 2005 Hydrologic Monitoring Data from the PPL Montana, LLC Process Pond System at Colstrip, Montana.

Rehm, B.W, G.H. Groenewold, and K.A. Morin. 1980. Hydraulic Properties of Coal and Related Material, Northern Great Plains. Groundwater, Vol. 18, No. 6.

Roberts, S.B, E.M. Wilde, G.S. Rossi, D. Blake, L.R. Bader, M.S. Ellis, G.D. Stricker, G. L. Gunther, A.M. Ochs, S. A. Kinney, J.H. Schuenemeyer, and H. C. Power. 1999. Colstrip Coalfield, Powder River Basin, Montana: Geology, Coal USDA-Farm Services Agency Aerial Photography Field Office. 2013. Montana 2013 NAIP Orthophotos, 1- meter resolution Rosebud County Montana (Imagery Date 7/21/13), Montana State Library. (ftp://ftp.geoinfo.msl.mt.gov/Data/Spatial/MSDI/Imagery/ 2013_NAIP/UTM_County_Mosaics)

Todd, D.K., 1980. Groundwater Hydrology. 2nd edition. John Wiley & Sons, New York, p. 535.

United States Environmental Protection Agency (USEPA). 1989. Statistical Analysis of Ground-water Monitoring Data at RCRA Facilities. Interim Final Guidance. Office of Solid Waste, Waste Management Division. April.

USEPA. 1994. Statistical Methods for Evaluating the Attainment of Cleanup Standards, Vol. 3: Reference Based Standards for Soils and Solid Media. EPA 230-R- 94-004. Washington, DC: Office of Policy, Planning, and Evaluation. http://www.epa.gov/swertio1/chartext_edu.htm#stats.

USEPA. 1998a. Statistical Analysis of Ground-Water Monitoring Data at RCRA Facilities: Unified Guidance. Draft. Washington, DC: Office of Solid Waste. http://www.epa.gov/swertio1/chartext_edu.htm#stats.

USEPA. 1998b. Statistical Tests for Background Comparison at Hazardous Waste Sites. Supplemental Guidance to RAGS: Region 4 Bulletins-Addition #1. Atlanta, GA. November. http://www.epa.gov/swertio1/chartext_edu.htm#stats.

U.S. Geological Survey (USGS), 2014. http://ca.water.usgs.gov /projects/central-valley/groundwater-modeling.html. Simulation Capabilities of MODFLOW. Accessed January 2015.

US Geological Survey (USGS). 2007. 24 K Topographic Quadrangles Colstrip West, Colstrip East, Colstrip Southeast, and Colstrip Southwest.

Van Voast, W.A. and J.C. Reiten. 1988. Hydrogeologic Reposes: Twenty Years of Surface Coal Mining in Southeastern Montana. Montana Bureau of Mines and Geology, Memoir 62, 30 pages.

Van Voast, W.A., R.B. Hedges, and J.J. McDermott. 1977. Hydrogeologic Conditions and Projects Related to Mining near Colstrip, Southern Montana. Montana Bureau of Mines and Geology, Bulletin 102, 43 pages.

Western Energy Company 2013a. 2013 Annual Mining Report Rosebud Mine Area A. Submitted to Industrial and Energy Minerals Bureau of the Department of Environmental Quality March 31, 2014.

Western Energy Company 2013b. 2013 Annual Mining Report Rosebud Mine Area B. Submitted to Industrial and Energy Minerals Bureau of the Department of Environmental Quality March 31, 2014.

Western Energy Company 2013c. 2013 Annual Mining Report Rosebud Mine Area C. Submitted to Industrial and Energy Minerals Bureau of the Department of Environmental Quality March 31, 2014.

Western Energy Company 2013d. 2013 Annual Mining Report Rosebud Mine Area D. Submitted to Industrial and Energy Minerals Bureau of the Department of Environmental Quality March 31, 2014.

Western Energy Company 2013e. 2013 Annual Mining Report Rosebud Mine Area E. Submitted to Industrial and Energy Minerals Bureau of the Department of Environmental Quality March 31, 2014.

Western Energy Company 2013f. 2013 Annual Hydrology Report Rosebud Mine. Submitted to Industrial and Energy Minerals Bureau of the Department of Environmental Quality February 2, 2014.

Western Energy Company. 2011. 2010 Annual Hydrology Report - Rosebud Mine

Western Regional Climate Center 2014. (Monthly and annual Average Pan Evaporation) Huntley Experimental Station (1911-2005) http://www.wrcc.dri.edu/htmlfiles/westevap.final.html#MONTANA

Younger P. L., Banwart, A.A., Hedin, R. S. 2002. Mine Water Hydrology, Pollution, Remediation. Kluwer Academic Publishers. Dordrecht, The Netherlands.