
**OTTER CREEK MINE
EXHIBIT 314C APPENDIX B
GROUNDWATER FLOW MODEL DEVELOPMENT,
CALIBRATION, AND MINE DEWATERING SIMULATION**

Prepared for:
Otter Creek Coal, LLC
Billings, MT

Prepared by:
Hydrometrics, Inc.
Billings, MT

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OTTER CREEK MINE
EXHIBIT 314C APPENDIX B
GROUNDWATER FLOW MODEL DEVELOPMENT,
CALIBRATION, AND MINE DEWATERING SIMULATION

1.0 INTRODUCTION

Hydrometrics developed a three-dimensional numerical groundwater flow model to simulate baseline groundwater flow conditions and predict hydrologic effects of the proposed Otter Creek Coal Tract 2 mine plan. Specifically, the model was constructed to accomplish six objectives.

1. Simulate pre-mine potentiometric head and groundwater flux through key hydrogeologic strata found in the Otter Creek Coal Tracts (i.e. Knobloch Coal, Otter Creek Alluvium, Clinker, and underburden aquifers) that are calibrated in steady-state to baseline hydrologic observations.
2. Simulate pre-mine surface water gains and losses in the Tongue River and reaches of Otter Creek adjacent to the Tract 2 mine area at baseflow. This simulation will be calibrated to surface water flow observations made in the months of September through November during the baseline hydrology study.
3. Evaluate groundwater inflow rates/dewatering rates to open mine cuts over the period of mine development to provide a basis for water management during mine operations.
4. Assess changes in groundwater levels (drawdown) due to mining in principal aquifers surrounding the mine area. These aquifers include Otter Creek alluvium, Knobloch coal, and two productive underburden aquifers. Specifically, the model will be used to predict the extent of the five-foot drawdown contour in each principal aquifer.
5. Assess post-mining water level recovery rates.
6. Evaluate potential for changes in groundwater-surface water interactions as a result of mining activities and quantify potential depletion effects on Otter Creek. This evaluation will be based on differences between steady-state pre-mining conditions and transient river leakage output for multiple time steps in the transient mine simulation.

Following the introduction, this report is organized according to the model development process, which was completed in six phases:

1. Conceptual Model Development;
2. Numerical Model Development;
3. Calibration to Steady-State Pre-Mining Baseline Conditions;
4. Flow Model Predictive Simulations – transient simulations of mine development and post-mining conditions;
5. Sensitivity Analysis; and
6. Evaluation of Model Results.

The flow model described herein does not address the fate and transport of chemical constituents in groundwater; thus, groundwater quality observations are not included in the model development process and projections of groundwater quality responses to mining are not made in this report. However, steady-state and transient flow budgets from zones delineated within and adjacent to the modeled mine area are used in water quality analyses presented in Section 6 of the Otter Creek Mine Exhibit 314C Probable Hydrologic Consequences.

Methodology and results of each phase of model development are discussed in separate sections; and conclusions of the groundwater flow modeling process are presented in the final section of this report. All phases of model development are parameterized by data and observations collected/made during baseline surface water and groundwater studies and/or previously published reports related to the hydrogeology of Otter Creek and the surrounding coal reserves. Attainment of the six modeling objectives, as they pertain to individual phases of model development, is documented in the following sections. Tables used to support model development, calibration, or evaluation of results are included in the body or are attached to the report. Figures are attached.

2.0 CONCEPTUAL MODEL DEVELOPMENT

The hydrologic framework used in the development of the numerical flow model is defined in the conceptual model; thus, conceptual model formulation generally includes identifying features that are important to a given hydrologic system and creating a list of variables that may have the greatest influence on the outcome of model simulations and attainment of model objectives. Variables of interest are related to areal properties and groundwater sources/sinks for the modeled aquifer(s). These parameters typically include recharge rates, aquifer hydraulic properties (storativity, transmissivity, confining layers, etc.), river bed conductance, and surface water interaction (i.e. Otter Creek) with groundwater, among others. The appropriate scale or extent of the conceptual model must also be selected, to accomplish specific modeling objectives. The conceptual model is largely qualitative but may also require calculations to characterize certain hydrogeologic processes (i.e. using groundwater potential at multiple wells to determine direction of groundwater flow). Conceptual groundwater flow models are often developed by evaluating geologic, topographic, and potentiometric maps, well logs, published results of previous studies, geologic cross-sections, and surface water and groundwater hydrographs. These tools were made available as a result of the baseline hydrologic investigation conducted at Otter Creek.

A map of the area included in the conceptual model and its relationship to the Otter Creek Mine Tracts is presented in Figure 2-1. The conceptual model encompasses a large regional area (approximately 354 square miles) because, per the model objectives, it is necessary to evaluate the potential for drawdown (out to five-foot contour) that may occur up to several miles from the mine. It is imperative to establish model extents and model boundaries in the development of the conceptual model that will later lead to attainment of objectives in the numerical model. Details of how model extents were projected and the conceptual hydrogeologic function of model boundaries are included in the following sections. A general overview of the hydrologic framework at Otter Creek and hydrogeologic parameters related to specific strata or source/sink features is presented in Section 2.1. Because one of the objectives of this modeling effort is to

predict the hydrogeologic response to coal mining, specifically mine de-watering, an abstract of the mining process is included in the conceptual model. This discussion is presented in Section 2.2.

2.1 BASELINE CONDITIONS

Figure 2-1 includes a depiction of major surficial geologic units (MBMG 428 and 431, 2001) including alluvium, clinker, and bedrock of the Tongue River Member of the Fort Union Formation. Knobloch coal is the first substantive water-bearing interval in the Tract 2 mine area. The coal is laterally connected with clinker beds on the margins of the Otter Creek valley, with Otter Creek alluvium, and ultimately with Otter Creek surface water. Together, these units create the most dynamic flow regime in the conceptual model and are the most likely to be influenced by mine dewatering. Underburden aquifers of the Fort Union Formation are important groundwater resources to local stakeholders and are used primarily for stock watering and domestic wells. These units are represented in the conceptual Otter Creek flow model but are expected to be influenced by mine dewatering to a lesser degree than the shallow flow system. The stratigraphic relationships of the principal units are illustrated in geologic cross sections in Map 16 (17.24.305(1)(y)). Hydrogeologic parameters, source/sink features, and flow patterns that are important to all strata contained in the baseline conceptual model are identified as follows.

2.1.1 Hydrostratigraphic Units

Knobloch Coal

The Otter Creek Coal mine will target the Knobloch coal, which is the primary coal of economic significance in the Otter Creek drainage. The Knobloch coal is nearly flat-lying, although the structure exhibits a shallow syncline which trends upward to the north and south. The axis of the syncline is in the middle of Tract 2 and at the south end of Tract 3. The axis is perpendicular to the boundary between Tracts 2 and 3; in this area the coal sub-crops and partially underlies the alluvium. Within the area encompassed by this modeling program, much of the coal seam is burned along the contact with alluvium, resulting in deposits of clinker. Saturated groundwater conditions are present throughout

most of the coal. Locally, groundwater flow in the Knobloch coal is apparently convergent with the Otter Creek alluvium. The direction of coal groundwater flow on the east side of Otter Creek is to the west/northwest. Groundwater flow in the coal aquifer on the west side of Otter Creek is divided along a north-south axis that coincides with a topographic divide created by King Mountain. From the divide, groundwater in the coal proceeds either east/northeast toward the Otter Creek drainage or west/northwest to the Tongue River drainage. A potentiometric surface map encompassing the entire conceptual model domain is presented as Figure 2-2. Water levels from baseline monitoring wells used to construct the map were recorded in October 2011 except for at wells A8, A9, and the B12 battery, which were not installed until summer 2014. Best publicly available data were used at other wells included in the map. The groundwater divide and general flow pattern is consistent with that mapped by the Montana Bureau of Mines and Geology (MBMG) (Wheaton, 2008) for Knobloch coal.

At the south end of Tract 2, the Knobloch coal is not found in one continuous deposit; rather, the coal is separated in up to four discrete seams. The uppermost seam is dry or minimally saturated south of Tract 2, as observed at well batteries B7 and B12. However, two saturated coal seams are present in the area south of the mine. Groundwater potential is not consistent between the seams. Water level elevations vary by as much as 100 feet at paired monitoring wells in the model domain (e.g. B8 battery); but flow from all of the Knobloch coal seams converges as the separated strata merge into a single body in the north. A potentiometric surface map constructed with limited data for the lower coal is included in Figure 2-3.

Separations in the Knobloch coal are presented in Map 16 (17.24.305(1)(y)). The cross-sections illustrate Knobloch coal and other bedrock sub-crop/outcrops on the Otter Creek valley margins. At the southern end of the valley within the model domain, a nearly complete section of Knobloch coal or entire sequences of lower saturated coal splits are present beneath the base of the Otter Creek alluvium. This is illustrated in cross-sections D-D' and H-H' of Map 16. Farther north (cross-section C-C'), the coal is burned on the valley margins (i.e. clinker is present) and is eroded by alluvium in the center of the

drainage. In some cases, alluvium directly overlays clinker of the Knobloch coal (cross-section C-C' and B-B'). The axis of the syncline in the Knobloch coal in the middle of the Tract 2 mine area extends into the alluvium, strengthening the lateral hydraulic connection between these two units immediately adjacent to the mine. As the elevation of the coal trends upward to the north, the coal and/or clinker outcrops above the elevation of Otter Creek and the alluvium. Cross-section A-A' shows lateral contact between alluvium and clinker; but the alluvium overlays underburden bedrock in the northern half of the model domain.

Most of the saturated coal behaves as a confined aquifer; but it is unconfined when directly adjacent to or beneath clinker and/or alluvium. Values of hydrogeologic properties (i.e. transmissivity, storativity, etc.) of coal are several orders of magnitude lower than those properties of the clinker and alluvium. Hydrogeologic properties calculated for the Knobloch coal are presented in Table 2-1 with the estimated range of groundwater flux through the Otter Creek Coal Tract 2 mine area and the larger model boundary to the east. Flux estimates were made based on a hydraulic gradient of 0.008 in the Knobloch coal; however, based on potentiometric observations in the coal, the gradient may range from 0.005 to greater than 0.01. The saturated thickness of the coal ranges from as low as 10 feet at wells completed in a single seam of the parted coal to 75 feet in the thickest portion of the merged seam. Hydraulic conductivity (K) values used in flux estimates range from 0.3 ft/day to 10 ft/day in the Tract 2 mine area and from 0.1 ft/day to 10 ft/day in the entire model area. The average K of the Knobloch coal in the mine area is 3.6 ft/day, as compared to an average model-wide K of the Knobloch coal of 2 ft/day. Also, there is an apparent trend of decreasing K from west to east across the mine area. K estimated at well B5-K, in the northwestern corner of the mine area, was 9.9 ft/day. K estimated at B6-K (the easternmost well in the mine area) was 1.0 ft/day. The minimum K estimated in the mine area was at well K-6 (0.3 ft/day).

Based on the wide range of hydraulic parameters presented in Table 2-1 the resultant flux estimates, for the Knobloch coal in the mine area, range from 5 to 585 gpm, with an

average of 157 gpm. Flux estimates across the larger model boundary, approximately 9.5 miles upgradient of the mine area, may range from 3 to 2599 gpm and average 312 gpm.

TABLE 2-1. KNOBLOCH COAL GROUNDWATER FLUX ESTIMATES

Knobloch Coal Groundwater Flux Estimates (Darcy's Law)											
Hydrogeologic Unit	Hydraulic Conductivity (ft/day)			Saturated Thickness (feet)			Boundary Length (ft)	Gradient (ft/ft)	Estimated Groundwater Flux (gpm)		
	min	max	avg	min	max	avg			min	max	avg
Knobloch Coal - Mine Area	0.3	10	3.6	18	75	55	19000	0.008	5	585	157
Knobloch Coal -- Model Boundary	0.1	10	2.0	10	75	45	83400	0.008	3	2599	312

Estimates of Knobloch coal aquifer storativity (S) ranging from 0.01 to of 1.6×10^{-4} (specific storage = 0.0009 ft^{-1} to $2.3 \times 10^{-6} \text{ ft}^{-1}$) were made based on pumping tests conducted during the baseline hydrology study. This value is consistent with the range of published storage coefficients reviewed by Rehm et. al (1980). As the coal is dewatered and unconfined conditions prevail at and near the mine cuts, specific yield (Sy) becomes an important parameter to characterizing groundwater flow. Based on published values, Sy of the coal is likely to range from 0.01 to 0.07 (Rehm, 1980).

Ephemeral Tributaries

East Fork Otter Creek, Home Creek, Threemile Creek, Tenmile Creek, and Fifteenmile Creek drainages each have their own alluvial groundwater flow component, some of which are equal in magnitude to flux through Otter Creek alluvium, and all of which discharge to Otter Creek alluvium. The surface water component from these tributaries is negligible however, because these streams are typically dry at baseflow conditions. On-channel pond P6 in the Tenmile Creek drainage approximately two miles from the confluence with Otter Creek is the only perennial surface water considered in any of the tributary drainages in the conceptual model because the elevation of the groundwater in nearby monitoring well A4 suggests a hydrologic connection between the ponded surface water and the shallow water table. A hydrograph of water levels measured at well A4 and pond P6 is presented in Figure 2-4. Note that the groundwater elevation at well A4 is

greater than that in the pond; and that water levels in A4 and P6 exhibit similar seasonal fluctuations. These observations suggest that the source of water in the pond, at least in part, is groundwater. Tenmile Creek drainage is dry below the pond except during spring runoff and isolated storm events.

The East Fork Otter Creek drainage is oriented such that it flows from northeast to southwest. This drainage is located at the north end of the area considered in the conceptual model. Surface topography and lithology of wells completed in this drainage suggest that alluvium in this drainage is hydrologically connected with the first shallow coal or bedrock aquifer. Aquifer properties in this drainage were not tested during baseline study; but it is assumed that they are consistent with properties of other nearby drainages.

The remaining four tributaries included in the model (Fifteenmile, Tenmile, Threemile, and Home Creeks) flow from east to west. Stream beds of these ephemeral drainages rise in elevation in the upstream (easterly) direction and become separated from the Knobloch coal groundwater system by overburden bedrock with very low permeability. Alluvial deposits in the ephemeral tributaries potentially have the greatest hydrologic effect on the Knobloch coal groundwater system near the tributary mouths where the two units are in direct hydrologic connection. Monitoring wells or well batteries are installed near the mouths of Home Creek (AVF-5 Battery), Threemile Creek (AVF-6 Battery), and Tenmile Creek (A4). Groundwater flux estimates in alluvium of these tributaries are included in Table 2-2.

TABLE 2-2. TRIBUTARY ALLUVIUM GROUNDWATER FLUX ESTIMATES

	Hydraulic Conductivity	Saturated Thickness	Boundary Length	Gradient	Estimated Groundwater Flux
Hydrogeologic Unit	ft/day	ft	ft	ft/ft	gpm
Home Creek Alluvium	77	50	1300	0.005	130
Threemile Creek Alluvium	90	34	1100	0.007	122
Tenmile Creek Alluvium	40	53	1100	0.005	61

Otter Creek Alluvium

Water-bearing sediments in the alluvium of Otter Creek and its tributary drainages consist primarily of poorly to well sorted sand and gravel originating from clinker and other sedimentary parent materials. Fine-grained sand, silt, and clay surface deposits are often present above the water-bearing sand and gravels. Depth to groundwater in the alluvium is typically less than 15 feet below ground surface (bgs). It is common for the shallow water level in the alluvium to rise above the contact of the fine-grained deposits and the gravel, which indicates that the alluvium may act as a semi-confined system. In general, groundwater flow in the alluvium is parallel to Otter Creek (flow from the southeast to northwest). Potentiometric maps are presented in the Baseline Report Exhibit 304E – Baseline Water Resources Data Report. As noted, the alluvium is often underlain by Knobloch coal or clinker (formed during in-situ burning of the Knobloch coal). Because of the disparity in permeability between alluvial deposits and coal, the alluvium is likely gaining where it is in direct contact with the coal. Conversely, alluvium in direct contact with clinker has the potential to drain to the more permeable thermally altered sediments.

Flux through Otter Creek alluvium is estimated in Table 2-3, based on aquifer properties calculated during the baseline study. K of Otter Creek alluvium varies widely depending on the texture/grain size of the saturated sediments. Wells on valley margins tend to be completed in finer-grained sediments and have lower K; whereas, wells completed in the center of the coarse gravel deposits (often more proximal to Otter Creek) have higher K. Actual alluvial flux will vary with valley width. Flux in the alluvium will likely increase in the downgradient direction as the valley widens and increased discharge to the alluvium is received from bedrock or alluvium of tributary drainages.

TABLE 2-3. OTTER CREEK ALLUVIUM GROUNDWATER FLUX ESTIMATES

Hydrogeologic Unit	Hydraulic Conductivity (ft/day)			Saturated Thickness (feet)			Boundary Length (ft)	Gradient *(ft/ft)	Estimated Groundwater Flux (gpm)		
	min	max	avg	min	max	avg			min	max	avg
Otter Creek Alluvium	3.4	554	135	14	70	31	3000	0.0028	1	1692	183

*average gradient of entire reach included in conceptual model; calculated as change in head between wells WO-7 and A9 divided by approximate distance between these points in direction of alluvial groundwater flow (~75,000 ft).

Clinker

Clinker is formed when sediments are exposed to intense heat from burning coal seams. When strata are thermally altered they typically become very hard and more rigid than similar sediments in an unaltered condition. As the coal burns, the volume of the seam decreases. The more rigid overburden subsides into the void left by the burned coal. Because it is inflexible, the rock fractures as the subsidence occurs. Fractures leave clinker well-drained and very permeable. As noted, large bodies of clinker are present within the model domain. Clinker bodies of most significance are those that are situated between alluvial valleys of Otter Creek and its tributaries and the unaltered Knobloch coal. Many of the other clinker bodies (see Figure 2-1) are isolated from the flow system modeled in this effort because they are associated with burns that are stratigraphically above the Knobloch coal aquifer and not in direct hydrologic connection. Clinker formations are illustrated in cross sections in Map 16 (17.24.305(1)(y)).

Hydraulically, clinker behaves as an unconfined aquifer; and certain deposits of these burned sediments effectively serve as a vast reservoir for groundwater storage along Otter Creek. Greater spacing between potentiometric contours (see figures in Baseline Report 304E) indicates that the hydraulic gradient across clinker is very low. Although this clinker is highly hydraulically conductive, flux through the unit can be no greater than the amount of water it receives from neighboring strata. Groundwater potential in the clinker is lower than in either the adjacent coal or alluvium; thus, both the Knobloch coal and

Otter Creek alluvium are potential sources of groundwater flow into the clinker.

An aquifer test was conducted in the clinker hydrogeologic unit where it is in direct hydraulic connection to the alluvium and bedrock at well C4. Well C4 was pumped at a rate of 360 gpm during the test for a duration of 100 minutes. There was no measurable drawdown detected in the pumping well using manual measuring devices and data obtained from electronic pressure transducer contained background “noise” that made it difficult to derive a definitive drawdown trend. A best fit line was generated for the electronically measured drawdown data using Aqtesolv analytical software. The resulting estimate of transmissivity was on the order of 762,000 ft²/day. There is some uncertainty in the transmissivity estimate generated from these data since manually measured drawdown was not detected; but the lack of drawdown at a high pumping rate clearly indicates that the clinker formation has a very high hydraulic conductivity and specific yield. A review of clinker aquifer testing results (Heffern and Coates, 1999) presents a range of clinker transmissivity in the Powder River Basin from 35,400 ft²/day to 1,482,400 ft²/day.

Overburden

Overburden is excluded from the conceptual model because it is thought to have little hydrogeologic influence on the shallow Knobloch/clinker/alluvium flow system and because overburden groundwater is not commonly targeted as a viable water resource by local stakeholders in the area of the proposed Otter Creek Mine. Based on observations made at monitoring sites included in the baseline hydrology study, groundwater in the overburden, where present, is low-yield, perched, and sparsely distributed (sometimes dry).

Interburden/Underburden

The thickness and composition of the interburden bedrock parting between primary Knobloch coal seam aquifers considered in the conceptual model is variable. Based on lithology at exploration boreholes and paired upper and lower Knobloch coal monitoring wells, the thickness of the separation is greater than 70 feet at the south end of the model

domain. Sedimentary rocks found in the interburden are composed of sandstone, siltstone, claystone, and/or shale interbeds; but the hydrologic connection between the parted seams is controlled by the fine-grained fraction of the interburden. Hydrologic properties of fine-grained interburden between Knobloch coal seams at the Otter Creek mine were not explicitly tested but are expected to exhibit parameters consistent with the range of published values for siltstone and/or shale. Siltstone hydraulic conductivity is low, ranging from 2.8×10^{-6} to 0.0039 ft/day (Domenico and Schwartz, 1991; Morris and Johnson, 1967). Siltstone specific yield varies greatly. Morris and Johnson (1967) present a range of 0.009 to 0.32, with an arithmetic mean of 0.12. Specific yield of siltstone and/or shale considered in the conceptual model is expected to be less than that of coal. As previously discussed, coal specific yield may range from 0.01 to 0.07 (Rehm, 1980). This implies a value of specific yield at the low end of the range submitted by Morris and Johnson (1967). Similarly, storage coefficients for the confined siltstone and shale are expected to be much lower than that of coal storage coefficients. Recall that the specific storage calculated for the Knobloch coal in the baseline study were as low as $2.3 \times 10^{-6} \text{ ft}^{-1}$.

The occurrence of groundwater in underburden of the Tract 2 area is variable. Based on observations made during drilling, well installation, and ongoing monitoring, potentially viable groundwater resources are found in two separate hydrostratigraphic intervals beneath the Knobloch coal. The first water-bearing bedrock interval occurs between 20 and 100 feet beneath the Knobloch coal and is coincident with a thin coal seam thought to be the Flowers-Goodale coal and/or a sandstone bedrock interval. Based on lithology observations made at monitoring wells installed during the baseline investigation, the thickness of this water-bearing interval ranges from eight to 53 feet. For the sake of the conceptual model, this unit is assumed to be laterally continuous across the model domain; however, lateral continuity of a horizon this thin is rarely observed in the Fort Union Formation over such a vast area.

The second underburden interval is a thicker, contiguous sandstone which has been encountered in the Otter Creek monitoring well network at depths between 159 feet and

224 feet beneath the Knobloch coal. Because of its depth and the presence of shallower groundwater in the overlying underburden, only three well batteries targeted this sandstone. The thickness of this sandstone observed in the Otter Creek monitoring network ranges from 38 to 90 feet.

Upper and lower underburden potentiometric surface maps were created using water level data from wells determined to be representative of each of the underburden aquifers listed above. The potentiometric surface map of the upper-most underburden layer (Flowers-Goodale) is presented in Figure 2-5. A map of the deep sandstone potentiometric surface is shown in Figure 2-6. Groundwater flux through the underburden units is calculated in Table 2-4. Based on the estimated direction of groundwater flow, flux is estimated for underburden aquifers through a cumulative boundary that includes flow from the south and east.

TABLE 2-4. GROUNDWATER FLUX THROUGH UNDERBURDEN AQUIFERS

Underburden Groundwater Flux Estimates (Darcy's Law)											
Hydrogeologic Unit	Hydraulic Conductivity (ft/day)			Saturated Thickness (feet)			Boundary Length (ft)	Gradient (ft/ft)	Estimated Groundwater Flux (gpm)		
	min	max	Avg.	min	max	Avg			min	max	Avg.
Flowers-Goodale Horizon	0.014	5	0.7	8	53	25	233400	0.005	0.7	1588	106
Sandstone Horizon	0.07	0.63	0.41	38	90	63	233400	0.002	6.5	138	63

Observations of lithology made at monitoring well batteries in the mine area indicate that in all cases bedrock that separates the Knobloch coal from the underburden aquifers contains at least some shale/siltstone confining or semi-confining layers. This finding is consistent with the assertion of Wheaton (2008) that numerous shale layers restrict vertical movement of groundwater between aquifers in the Fort Union Formation.

Hydraulic properties of underburden siltstone and shale are expected to be consistent with those previously discussed for interburden.

Potentiometric maps presented in the Baseline Report 304E – Baseline Water Resources Data Report indicate instances of higher groundwater potential in the underburden than in the coal (i.e. an upward gradient) in areas of Tract 2 coincident with proposed mining operations. Shale separation coupled with the upward vertical gradient will limit the influence that stresses to the Knobloch coal (i.e. dewatering) have on the lower aquifers. Finally, the beds of impermeable material are assumed to limit the interaction between underburden aquifers and Otter Creek Surface flows. Based on recorded elevations of the underburden beds, they do not outcrop or sub-crop along or beneath the Otter Creek Alluvium. This is similar to the assumption made in an early modeling effort by Cannon (1985).

2.1.2 Groundwater/Surface Water Interactions

Otter Creek

Otter Creek is the primary surface water feature of interest in the mine area and model domain. Otter Creek is a perennial stream that originates in south Powder River County and flows north to the Tongue River at Ashland, MT. Tracts 1 and 2 of the proposed Otter Creek Coal Mine are located to the east of Otter Creek, and Tract 3 is located on the west side of Otter Creek, between eight and nine miles from its confluence with the Tongue River. Otter Creek and its tributaries near and within the mine are pertinent to the groundwater modeling effort due to their hydraulic connection with the Knobloch coal. Alluvium, and ultimately surface water in Otter Creek and its tributaries, is either in direct connection with the coal or is laterally connected to the coal by permeable clinker deposits. Stratigraphic cross sections, illustrating connectivity of Otter Creek and key subsurface strata, are presented in Map 16 (**17.24.305(1)(y)**). It should be noted that, while there is a hydraulic connection between Otter Creek and its alluvium, much of the Otter Creek stream bed is composed of very fine-grained silty/clayey sediments that limit conductivity between surface water and the underlying alluvium.

Due to contributions from ephemeral drainages and additional groundwater discharge, Otter Creek is generally a gaining stream in the reach that is included in the conceptual model. However, there are smaller sections of the stream that may be losing reaches based on their position relative to highly permeable clinker deposits. The modeled reach of Otter Creek extends from approximately one mile south of Fifteenmile Creek to the confluence with the Tongue River north of Ashland, MT.

Otter Creek is not presently gaged at the upstream end of the modeled reach (i.e. from Fifteenmile Creek to Tenmile Creek); however, observations made at surface water sites SW-22, SW-16, and USGS gaging station 06307740 (Otter Creek at Ashland MT) were used to characterize Otter Creek stream flow conditions in the model. Stream flow observations collected in Fall of 2011 and 2013 at these sites are presented in Table 2-5. Stream flows at the downstream endpoint (USGS gaging station 06307740) considered in this conceptual model ranged from 4.4 to 6 cfs. Flow at upstream sites ranged from 2.1 to 5.5 cfs. These flow observations are representative of baseflow conditions for higher than average water years, as were each of the years during which baseline study was performed. For example, the mean daily flow for October 26 at USGS gaging station 06307740 is 1.8 cfs for the period of record (32 years). Mean daily flows at the same site for years 2011, 2012, and 2013 were 5.9 cfs, 3.7 cfs, and 4.9 cfs, respectively. Although the stream flow observations presented in Table 2-5 are greater than average baseflow conditions, they provide a quasi-synoptic set of surface water observations when coupled with groundwater level observations made in late October 2011.

The modeled reaches are illustrated in Figure 2-7. The reach between SW-22 and SW-16, identified as Reach 2, is a losing reach based on these measurements. Average stream loss over this length of Otter Creek is 0.9 cfs; but loss estimates range from 0.1 to 2.4 cfs. Changes in surface water flow due to baseflow contributions in this reach are minimal because water that discharges to the stream from the Knobloch coal at the upstream end of the reach is later lost to clinker on the Otter Creek valley margins. Observed gains in Reach 3, from SW-16 to the USGS gaging station, range from 2.3 to 2.9 cfs. The average gain throughout this reach is 2.6 cfs under the conditions observed during the baseline

hydrology study. Further description of Otter Creek and other surface water features is included in the baseline characterization report (304E).

TABLE 2-5. ESTIMATED STREAM FLOW GAINS AND LOSSES OTTER CREEK

Date	Flow (cfs)			Gain/Loss (cfs)	
	SW-22	SW-16	USGS	Reach 2 SW-22 to SW-16	Reach 3 SW-16 to USGS
			06307740		
10/22/2013	2.6	2.2	5.1	-0.4	2.9
11/3/2011	5.5	3.1	6	-2.4	2.9
10/26/2011	4.2	3.6	6	-0.6	2.4
9/29/2011	2.2	2.1	4.4	-0.1	2.3
Average gain/loss (cfs)				-0.9	2.6

Tongue River

The Tongue River flows from south to north and provides a tangible hydrologic boundary on the west edge of the model. Although the Tongue River is not expected to be directly influenced by mining in Tract 2, due to its distance from the mine and the hydrologic buffering effects of Otter Creek, the Tongue River is a regionally significant surface water feature in the model area and is the receiving water for surface discharge from Otter Creek. Unlike Otter Creek, which has minimal contribution from deeper aquifers, the Tongue River receives abundant groundwater discharge from the Tongue River Member of the Fort Union Formation. Wheaton et al. (2008) cites (Woods, 1981; Vuke and others, 2001a; Vuke and others, 2001b) in submitting that the Tongue River receives approximately 23 cubic ft per second (cfs) of ground-water discharge between the Tongue River Dam and the Brandenburg bridge. Stream flows in the reach of the Tongue River included in the current conceptual model are well catalogued by two USGS gaging stations: USGS 06307616 Tongue River at Birney Day School Bridge near Birney, MT at the upstream end of the reach; and USGS 06307830 Tongue River below Brandenburg Bridge near Ashland, MT. The latter site is approximately 17 miles downstream (north) of Ashland and the model domain; however, a comparison of flows between the two sites provides an indication of the rate of gain in the modeled reach from Birney to Ashland,

MT. A hydrograph of average stream flows for the matching period of record between the sites, for the time period from August to January, is presented as Figure 2-8. The hydrograph indicates that the Tongue River is a gaining reach during the baseflow conditions considered in the conceptual model.

Stream gains calculated from the data presented in Figure 2-8 are summarized in Table 2-6. The long-term average gain in surface flow from Birney to Brandenburg for the period from September 15 to December 1 is 25 cfs. The estimated long-term minimum and maximum gains in the same reach are 10 and 41 cfs, respectively. The distance from Birney to Brandenburg is approximately 59 river miles; which indicates that the Tongue River gains between 0.17 cfs and 0.69 cfs per mile. Groundwater discharge to the Tongue River from the conceptual model domain is limited to one side of the river (i.e. from the east); thus, the estimated rate of groundwater contribution to the Tongue River from the model domain is half of the total rate of gain (a range of 0.085 cfs/mile to 0.35 cfs/mile).

TABLE 2-6. TONGUE RIVER GAINS FROM BIRNEY DAY SCHOOL TO BRANDENBURG BRIDGE

River Reach	Average Gain for Period of Record (cfs)			Length of River Reach (miles)	Rate of gain (cfs/mile) /2		
	min	max	avg		min	Max	avg
USGS Birney Day School to Brandenburg Bridge	10	41	25	58.6	0.09	0.35	0.22

2.1.3 Recharge

An annual recharge rate of 1.54 inches (0.00035 ft/day) was calculated for non-sub-irrigated alluvium and clinker in the Otter Creek valley by Cannon (1985). Alternatively, Woessner et al. (1981) calculated annual recharge rates of 1.2 inches and 2.8 inches (0.00027 ft/day and 0.0006 ft/day) in the clinker and alluvium, respectively. Recharge to the Knobloch Coal occurs at a much lower annual rate than does recharge to shallow alluvium and clinker units. Estimates of annual recharge to the coal range from 0.01 inches to 0.1 inches (2.28×10^{-6} ft/day to 2.28×10^{-5} ft/day) (Cannon 1985). However,

actual coal recharge rates will vary with depth to coal, thickness and texture of overburden, amount of precipitation, and proximity to outcrops. Numerous publications cite increased recharge to Fort Union bedrock aquifers where clinker capped ridges are present (Heffern and Coates, 1999; Wheaton et al., 2008; Meredith, 2012). As seen in Figure 2-1, clinker (although topographically isolated from the saturated groundwater flow system) is present across much of the model domain.

2.2 COAL MINE OPERATIONS, DEWATERING, AND RECOVERY

To simplify the conceptual mine dewatering model, an abridged version of the mine plan is presented in Figure 2-9. The figure includes only the immediate Tract 2 Mine Area, water handling ponds, and the 19-year sequence of mine development. This abridged version of the mine plan provides enough details to adequately formulate the critical hydrologic concepts of mine dewatering and allows for effective transfer of ideas from the conceptual model to the numerical model.

Constructs of transient simulations will include dewatering the Knobloch coal. In accordance with the Operational Groundwater Management plan outlined in section 3.2 of Exhibit 314A: Protection of the Hydrologic Balance, groundwater encountered in pits will be handled as follows.

- Pit inflow water will be managed internally to avoid discharge to Otter Creek:
 - During initial box cut development, pit inflow water will be pumped to an excavated pond in the mine plan footprint.
 - As the box cut is developed, water will be pumped or routed to in-pit sumps.
 - As the dragline pit advances, pit water will be routed via ramp road ditches to box cut ponds established in backfilled spoils.

The concepts outlined above are developed further to make them more applicable to the groundwater modeling effort.

- Mining will commence by removing overburden and exposing the coal in the sequence illustrated in Figure 2-9.
- As groundwater is encountered, it will be removed by pumping from the current

open pit. Open pits will be roughly 400 ft x 1000 ft and extend to the bottom of the Knobloch Coal.

- During the first two years of mining, groundwater pumped from open pits will be routed to an unlined holding pond, located in the center of the Tract 2 mine area as identified in Figure 2-9.
- As mining advances, spoils derived from overburden will be returned to previously mined pits.
- In subsequent years of mining/mine dewatering, the location of holding ponds will be moved such that they are positioned on mine spoils in the backfilled pits.
- In addition to storing water removed from mine cuts, the holding ponds will store water from direct precipitation and/or surface runoff from contributing upland area or ephemeral drainages.
- Water that is routed to the holding ponds (by pumping or runoff) will either evaporate or infiltrate. The fate of infiltrated water will be spatiotemporally dependent. Some fraction of groundwater that infiltrates through ponds near the active mine area will likely be re-circulated in the mine dewatering process.
- This groundwater management strategy will not only eliminate discharge to Otter Creek but will mitigate potential depletion effects on the creek by creating a hydrologic barrier between pit dewatering and the stream.
- During and at the conclusion of mining, groundwater will flow from areas of higher head toward the depressed mine area aquifer, recharging the spoils over time. The permeability of spoils is highly variable and will affect the rate at which water levels will recover.

2.2.1 Spoils Properties

Since the mine spoils will replace the coal in the backfilled workings, the hydraulic properties of the spoils will potentially influence drawdown effects during mine operations as well as effect the rate of groundwater recovery in the reclaimed mine area. Spoils in the Northern Great Plains generally have a K less than the coal, but similar to the silt, sand, and clay overburden (Rehm et al., 1980). The K of the spoils, however, can be highly variable, ranging over six orders of magnitude with a 1.5 order of magnitude standard deviation. Rehm et al. (1980) reports a geometric mean of 0.25 ft/day for 40 spoils K values. Eleven of these samples were from a summary of hydrogeologic

conditions in the Colstrip, MT area (Van Voast et al., 1977) in which the range of spoils K is 0.04 ft/day to 5.6 ft/day. Spoils in the Colstrip, MT area are of consistent parent material and are likely to be similar in hydrogeologic properties to those at Otter Creek. Note the K of Colstrip, MT spoils are actually consistent with the range of K calculated in the baseline study for undisturbed coal aquifers in the Otter Creek area.

During the initial period of water level recovery during and following mining, the once confined coal aquifer will behave as an unconfined water table aquifer in the spoils. For this reason, specific yield (Sy) of the spoils may greatly influence early water level recovery rates. Sy is essentially equal to the effective porosity of the spoils and commonly ranges from 0.1 to 0.3 for water table aquifers. Values of Sy could vary significantly within this range depending on the texture of the spoil parent material and the internal structure of the redistributed spoils. For example, spoils may be deposited as highly compacted fine-grained sediments or may be cast-blasted as blocky loose boulders.

2.2.2 Spoils Recharge

Recharge to the spoils will occur primarily as lateral flow from the undisturbed coal aquifer to the east and potentially more so from the alluvium/clinker to the west. This flow pattern is expected to persist during mining and in the post-mine environment until depressed water levels in the mine area rise to levels that will restore the direction of groundwater flow to that seen in pre-mine conditions. Recharge from the Otter Creek side will be controlled to a degree by a 500-foot coal buffer, left in place between native clinker or alluvium and the mine area.

During mining, variable cover thickness of heterogeneously mixed overburden (spoils) may create isolated zones of increased recharge from precipitation to the spoils aquifer. Also, the mine water handling strategy dictates that water removed from the coal mining area will be placed in holding ponds that are situated either on top of undisturbed overburden or on spoils behind the advancing mine. Water placed in holding ponds on top of undisturbed strata will likely have little influence on recharge and/or mine

dewatering rates; but some fraction of the water held in ponds constructed of spoils is likely to re-circulate into mine workings.

2.2.3 Analytical Projections of Drawdown from Mine Dewatering

A line sink analysis was conducted during conceptual model development to project a distance-drawdown relationship in the Knobloch coal aquifer due to mine dewatering. Results of the preliminary projections were used to loosely define the geographic area that is included in the model (presented in Figure 2-1). Ultimately, these projections were used to set the distance from the mine area to boundary conditions in the numerical model. Appropriate placement of model boundaries is important in any modeling effort and is critical to the attainment of Objective 4 in the current model.

The successive steady-state finite-length line sink algorithm of Koch (1986) was selected to make radius of influence projections from dewatering at Tract 2 of the Otter Creek mine. This analytical expression employs the theory of superposition and a semi-empirical relationship for the radius of influence to predict drawdown with reasonable accuracy at near steady-state conditions. Equations (Koch 1986), variable definitions, and parameter assignments used in this analysis are presented in Figure 2-10.

Hydrologic properties consistent with those described previously in the conceptual model were used in the calculations. A transmissivity of 100 ft²/day and a storativity of 0.0001 were assigned to the model. A representative mine cut of one mile in length was assumed in the calculation. According to the mine plan, individual mine cuts will have dimensions of 1000 ft x 400 ft and will extend in depth to the base of the Knobloch coal. Mine dewatering was simulated by assuming a maximum drawdown of 136 feet at the line sink. This is analogous to a 68-foot thick coal seam with potentiometric head that rises 68 feet above the top of the seam due to confined conditions. This maximum drawdown assignment is consistent with, but slightly greater than, the water column in the coal at the eastern edge of the mine area. By assuming a maximum dewatering depth estimate at steady state conditions, the solution should yield an overestimate of the actual drawdown effects and provide a conservative estimate of the overall radius of influence.

The line-sink equation was re-arranged to solve for discharge (Q) to the mine pit for a given drawdown of 136 feet; then, the distance-drawdown relationship extending normal to the line-sink was projected for a period of 365 days. None of the proposed mine cuts are expected to undergo continuous dewatering for an entire year; and steady-state drawdown conditions will not be realized at any point during mine dewatering. However, a period of 365 days was used to fulfill the assumption of near steady-state conditions in the analytical model. After 365 days, the distance to the five-foot drawdown contour is estimated at 33,686 feet (6.4 miles) and the radius of zero influence is projected to 38,210 feet (7.2 miles). Dewatering rates (discharge to the pit) decrease from 608 gpm to 130 gpm from one to 365 days in the analytical solution.

The analytical methods of Koch (1986) are limited by assumptions of aquifer homogeneity and infinite extent. Also, the application of this method to estimate cumulative drawdown effects of multiple sinks would require intense manual computation. However, this method does provide a useful approximation of the area to be considered in the conceptual model and provides a starting point for determining an appropriate relationship between model boundaries and mine features in the numerical model.

3.0 NUMERICAL MODEL DEVELOPMENT

Parameters introduced in the development of the conceptual model were used to populate a three-dimensional numerical flow model as described herein. Model code selected for the numerical modeling effort was MODFLOW-2005 (Harbaugh, 2005). MODFLOW-2005 is an updated version of the modeling code commonly called MODFLOW. MODFLOW was originally documented in 1984 (McDonald and Harbaugh, 1984); but the most robust presentation of the computer program and associated code was released in 1988 (McDonald and Harbaugh, 1988). The model was updated in MODFLOW-2000 (Harbaugh et al., 2000) to contain an expanded modularization approach, including additional data input capabilities and multiple equations not found in MODFLOW (McDonald and Harbaugh, 1988). MODFLOW-2005 is similar in construction to MODFLOW-2000. This model simulates physical two- or three-dimensional groundwater flow through porous media via a finite-difference numerical algorithm. Where applicable, simulation of hydrologic stresses (sources/sinks) are input to the model via individual packages and are included in the finite-difference equation. Rivers and drains are examples of physical features that are handled in the model via source/sink packages. Since its release, MODFLOW has been widely used and highly validated in numerous groundwater flow applications, such that it has become the industry standard for two and three-dimensional finite difference groundwater flow modeling.

The graphical user interface Groundwater Modeling System (GMS) 10.0 © 2014 was used to process MODFLOW-2005 input data and to evaluate model output. The GMS graphical user interface is analogous to a geographic information system (GIS) and allows for users to input layer data that may include map features. Hydrologic features mapped in GMS are converted to MODFLOW-2005 (Harbaugh, 2005) input packages.

3.1 MODFLOW BASIC PACKAGE, FLOW PACKAGE, AND SOLVER

The Basic Package was used to convert GMS map layers into data arrays and assign those arrays to MODFLOW grid cells. The Basic Package reads initial input and boundary conditions, implements stress periods and time steps (for transient simulations),

calculates overall water budgets, and controls output at the user's command (McDonald and Harbaugh, 1988).

Three packages, the Block Centered Flow (BCF) package, the Hydrologic Unit Flow (HUF) package, and the Layer Property Flow (LPF) package, are available in MODFLOW for calculating internal (cell-to-cell) flow. The LPF package was chosen for this simulation and is appropriate based on the vertical discretization of the model and the need for a fully convertible cell type. The LPF and HUF packages are very similar in their implementation but the HUF package allows geometry and properties of hydrogeologic units to be independent of model layer assignment. Layer properties are calculated internally (averaged) of all of the hydrogeologic units that are present in a given layer. Model layers in the HUF package are assumed to be nearly horizontal. Layer geometry in the LPF package can be assigned to conform more closely to physical stratigraphy and hydrologic property arrays are assigned by the user to each layer. All of the flow packages allow for convertible cells (allowing conversion from confined to unconfined flow conditions); but the BCF package requires more user input in regard to cell type. In convertible cells, the flow package calculates transmissivity of the fully saturated cell under confined conditions (i.e. when the water level is above the top of the cell); but if the water level drops below the top of a given cell, transmissivity is automatically calculated based on head in the cell, cell saturated thickness (calculated from head and cell bottom elevation) and the user specified hydraulic conductivity. Convertible cells are necessary in the transient simulation when mine dewatering lowers water levels in the aquifer adjacent to the mine. In this circumstance, if adjacent cells did not automatically convert to water-table (unconfined) cells, an artificially high transmissivity and pit dewatering rate would occur.

A cell re-wetting routine is optional for convertible cells in the LPF package; however, re-wetting was not used in the transient dewatering simulations in this numerical model. Conversion from dry to wet in a given cell is based on a wetting threshold and head in laterally or vertically adjacent cells. The wetting threshold is user-specified and requires a trial and error approach to attain appropriate parameterization. Ultimately, wet/dry

conversion may lead to numerical instability in the model (Harbaugh, 2005). Instead of allowing cells to go dry during transient mine dewatering simulations, drains were set at a minimum of 0.5 feet above the layer bottom elevation.

Similar to the transmissivity calculation for convertible layers, the storage contribution to the flow equation is determined from confined and/or unconfined storage, depending on head compared to the top elevation of cells. Values of both specific storage (Ss) and Specific yield (Sy) are specified for each cell in the model. Specific-storage values are multiplied by cell volume to obtain storage capacity for confined conditions, and the specific-yield values are multiplied by cell area to obtain storage capacity for unconfined conditions (Harbaugh, 2005). MODFLOW automatically uses the appropriate value, depending on head conditions in a given iteration.

Three different solver packages are offered in MODFLOW-2005 to solve the finite difference flow equation: the Strongly Implicit Procedure (SIP) package, Direct Solver (DE4) package, and the Preconditioned Conjugate-Gradient (PCG) package. Two versions of the PCG package are available in GMS 10.0, namely the Preconditioned Conjugate-Gradient 2 (PCG-2) and the Preconditioned Conjugate-Gradient with Improved Non-Linear Control (PCGN). All of these solvers use an iterative approach, whereby incrementally more accurate partial solutions of the flow equation result from repeated calculations. Each of the solvers listed above implements iteration differently; and the applicability of a given solver is typically a function of the size and complexity of the flow problem. It is up to the user to decide which of the solvers will solve the equations in a given simulation and how much computing time is allowable for each solution. Users must also specify convergence criteria for each of the solvers; and specify the maximum number of iterations per stress period if convergence criteria are not met.

The PCG2 solver package was selected for this modeling application. The PCG2 package has a more robust iterative scheme than the SIP package and is less computationally demanding than the DE4 package. Convergence criteria for the SIP and

DE4 packages are limited to head change criteria; while, the PCG2 package also includes a residual criterion for convergence. The residual criterion for convergence is related to the flow budget; convergence is not attained until the maximum absolute value of the residual at all nodes in the iteration is less than or equal to the residual convergence criterion (Hill, 1990). PCG2 package input applied to steady-state and transient solutions are found in Table 3-1.

**TABLE 3-1. PRECONDITIONED CONJUGATE-GRADIENT 2 SOLVER
PACKAGE INPUT**

Parameter	Value
Maximum number of outer iterations	100
Number of inner iterations	100
Head change criterion for convergence	0.01 ft
Residual criterion for convergence	0.01 ft ³ /day
Relaxation parameter	0.97
Damping	1.0

The maximum number of outer iterations and the number of inner iterations was assigned a value of 100. This relatively high number of iterations was helpful during early model runs because it allowed for meaningful computation even in the absence of convergence. By evaluating output files of early non-convergent model runs, Hydrometrics was able to identify shortcomings in preliminary parameter assignment and make changes that would advance model stability and convergence. Once a stable model was developed, the number of iterations needed by the solver did not approach the maximum allowed. Head change and residual convergence criteria were assigned values of 0.01 ft and 0.01 ft³/day, respectively. These parameters are commonly used with preconditioned conjugate-gradient solvers (Hill, 1990) and are the default values in GMS. The Modified Incomplete Cholesky method is the default preconditioning method in GMS 10.0 and was applied to the PCG2 package in the current modeling effort. The origins and use of this preconditioning method in MODFLOW are discussed by Hill (1990). The relation and damping parameters are associated with preconditioning. The default for each of these

parameters is 1.0; however, for some flow problems a relaxation parameter value of 0.99, 0.98, or 0.97 will reduce the number of iterations required for convergence (Hill, 1990). The damping parameter was not changed from the default; but the relaxation parameter was set at 0.97 throughout the model development process.

3.2 MODEL DOMAIN

The active model domain encompasses an area of approximately 354 square miles. In terms of physical features, the model extends along a boundary formed by the Tongue River from Birney, MT in the southwest to Ashland, MT and the Otter Creek/Tongue River confluence in the northwest. The eastern model boundary extends from south to north along a line that is nearly parallel to and offset approximately 10 miles from the eastern edge of the Tract 2 mine area. This boundary is coincident with headwaters of the major tributary drainages to Otter Creek; and it was offset from the mine area to allow prediction of the five-foot drawdown contour inside the model domain. The 10 mile offset is roughly 1.5 times greater than the zero-radius of mine influence projected by the previously mentioned analytical solution. The southern boundary of the model connects the east and west model boundaries along a line that is approximately one mile south of Fifteenmile Creek. The northern model boundary extends laterally from Ashland, MT to Suicide Pass. The long axis of the model domain (west to east) is approximately 150,000 feet (28.4 miles); from north to south the model is roughly 83,400 feet (15.8 miles) in length; and the model is approximately 129,250 feet (24.5 miles) in length along the general direction of groundwater flow from southeast to northwest.

Initially, a rectangular model grid (184 cells by 331 cells) was framed around the selected model domain. This grid was truncated from its initial rectangular shape by de-activating cells outside of the model boundaries. The irregular-shaped grid presented in Figure 3-1 was the result. A uniform 500-foot grid spacing, appropriate for the regional domain, was used in the model. A more refined grid would result in added computational complexity but would not translate to further meaningful precision in model output. Stresses applied in the transient model occur at drains that typically have an area larger than a single 500 ft x 500 ft cell; thus, water levels calculated for drains are not overly

averaged with cells that do not have drain properties. Drains used to simulate mine dewatering are discussed in detail in Section 3.7 of this report.

3.3 VERTICAL DISCRETIZATION

As previously noted, one objective of this modeling effort was to predict aquifer responses to mine dewatering in the Knobloch Coal (both inside and outside the mine area), alluvium, clinker, and underburden aquifers. Nine cell layers were used in the model to define these primary aquifers and the surrounding lower permeability strata, where present. Layers were defined in the 3-D model as summarized in Table 3-2. Model layers were vertically discretized in this manner to provide a more comprehensive analysis of flow conditions between major hydrostratigraphic units and to add numerical stability.

TABLE 3-2. MODEL LAYER SUMMARY

Layer Number	Description, lithological assignment
1	Shallow groundwater flow system consisting of Knobloch coal, clinker, and alluvium
2	Interburden between upper and lower Knobloch coal in south half of model, coal in majority of northern half of model, alluvium where appropriate, coal at Knobloch sub-crops in Otter Creek alluvium
3	Lower Knobloch coal in south half of model, underburden in northern half of model, alluvium where appropriate
4	Underburden aquitard, moderate hydraulic conductivity (interbedded sandstone/siltstone/shale)
5	Underburden aquitard, low hydraulic conductivity (shale)
6	Flowers-Goodale and other underburden bedrock aquifer
7	Underburden aquitard, low hydraulic conductivity (shale)
8 & 9	Lower sandstone aquifer, consistent properties applied to both; Layer 9 is included for added model stability

Layer elevations were estimated by integrating publically available lithology information for the greater model domain with lithology information collected during monitoring well installation and exploration borehole drilling in the more local Tract 2 study area. Lithology data were used to prepare 11 spatially accurate fence diagrams oriented east-west across the model domain. Lithologic units were correlated in the fence diagrams and assigned to one of the nine layers identified in Table 3-2. Scatter point arrays of top and bottom elevations for each layer were generated from the correlated cross-sections and imported into GMS. The scatter points were interpolated to MODFLOW layers using a nearest neighbor interpolation. Representative model cross sections are presented in Figure 3-2. Structure contour maps of model layer bottoms are shown in Figure 3-3. Note that the shallow syncline feature is mapped in each layer of the model; but its influence decreases with depth as the lower layers dip more uniformly to the northwest.

Representative model cross-sections (Figure 3-2) were chosen to illustrate key details in layer relationships, such as Knobloch coal outcrops/sub-crops in the Otter Creek alluvium, Knobloch coal splits, and mine area lithology. Portions of Otter Creek alluvium with full/partial sections of Knobloch coal immediately beneath the alluvium are represented in the model, as shown in cross section D-D' of Figure 3-2. Separations in the Knobloch coal at the south end of the model are simulated by the coal-interburden-coal sequence in layers 1 through 3. Where the Knobloch Coal is split in the area of mine development, layers 1 through 3 are consolidated by manually thinning layers 2 and 3; hence, layer 1 is approximately as thick as an entire section of separated coal in the south end of the mine area. Model cross sections C-C' and F-F' illustrate how the Knobloch coal was modeled in the mine area. Note that Layers 2 and 3 thin gradually as they dip towards the mine area. A gradual decline was created in the model layers because abrupt changes in cell layer elevations and or cell geometry may result in loss of continuity in the finite difference flow equation used in MODFLOW. This vertical discretization of Knobloch coal layers promotes numerical stability in the model but also exaggerates the hydraulic connection (both horizontally and vertically) between coal aquifer Layers 1 and 3. Layers 2 and 3 remain thin (approximately 3 feet thick each) in the northern half of the model where the Knobloch coal is present in a single body.

3.4 HORIZONTAL DISCRETIZATION

Layer 1 Areal Properties

Layer 1 was delineated into one of three hydrogeologic units (Knobloch coal, alluvium, or Clinker), each assigned values of aquifer properties (i.e. hydraulic conductivity, specific storage, and specific yield) consistent with those determined by onsite aquifer tests or other valid published results. The parameter zonation was conducted using a combination of geologic maps and field verified clinker and alluvium boundaries. Final parameters were selected iteratively from the appropriate range of parameters discussed in the conceptual model for each lithologic unit. A total of 39 areal parameter zones are assigned in Layer 1. A summary of parameters used in Layer 1 is presented in Table 3-3, attached. Parameter zones listed in the table are illustrated in Figure 3-4.

Notable parameter zonation assignments for each hydrogeologic unit type are as follows:

- Knobloch coal –
 - Average hydraulic conductivity of coal in the mine area, especially on the west side near crop lines or burn lines, is greater than the average of all wells tested in the study area. Recall that the average mine area K is 3.6 ft/day; but localized K as high as 10 ft/day were estimated. During model development, K was varied iteratively within the observed range to represent the potential trend of greater than average values in the area of mine development. A final K of 4.75 ft/day was applied to the northwest portion of the mine area.
 - A K of 2.0 was assigned to the northeast portion of the mine area and to much of the model domain northeast of the mine area. This value is consistent with the average Knobloch coal K estimated during baseline study.
 - The southern half of the mine area has separated coal seams in the physical system that are simulated as a single layer in the model. Therefore this “coal” layer was assigned a slightly lower K of 1.5 ft/day so as not to introduce artificially high transmissivity into the model.

- K values representative of coal for the rest of the Layer 1 model domain ranged from 0.5 to 10 ft/day, as shown on Figure 3-4 and Table 3-3.
- A specific storage value of 2.3×10^{-6} ft⁻¹ and specific yield of 0.05 were assigned to all coal parameter zones. The low specific storage was assigned to provide conservative drawdown estimates in transient simulations.
- Parameter zone 12 is located between the mine area and Otter Creek Alluvium. This zone is representative of an unconsolidated sand and gravel deposit, encountered during exploration drilling, that directly overlays the Knobloch coal. A composite K of 20 ft/day was assigned to this polygon in Layer 1. The storage coefficient of this zone was increased by a factor of ten to 2.3×10^{-5} and specific yield was increased to 0.12.
- Alluvium –
 - Hydraulic conductivities assigned to parameter zones representative of Tongue River alluvium, Otter Creek Alluvium, and alluvium of tributary drainages ranged from 30 ft/day to 250 ft/day in Layer 1, as presented in Figure 3-4 and Table 3-3. Alluvium parameter zones were uniformly assigned storage coefficient and specific yield values of 0.00092 and 0.22, respectively.
 - Alluvial properties that were applied to the model along tributary drainages of Otter Creek in Layer 1 were not extended to the eastern edge of the model domain; instead, these properties were only applied to areas representative of mouths of drainages that are in direct hydraulic connection with the Knobloch coal. In the physical system, the relatively flat lying coal becomes hydrologically separated from the alluvium by an increasing thickness of low permeability overburden bedrock as the valley bottom elevation climbs to the east.
 - The parameter zone representative of East Fork Otter Creek alluvium is the exception. The surface topography, and presumably the gradient in shallow groundwater, trends from northeast to southwest in this drainage.

Where this drainage crosses the north model boundary, alluvium is assumed to be laterally connected to the bedrock/coal aquifer in Layer 1. A general head boundary, discussed further in Section 3.5, was assigned at the upgradient model boundary to provide flux to East Fork Otter Creek alluvium.

- Clinker –
 - Clinker properties were not universally assigned to all clinker bodies present on published geologic maps (e.g. Figure 2-1). In fact, interpreting the amount of clinker and its connection to the hydrogeologic system of Layers 1 through 3 was one of the most difficult challenges in attaining a stable numerical model. Clinker cells tend to drain surrounding cells because hydraulic properties assigned to clinker cells are much higher than neighboring coal cells. The draining effect leads to dry coal cells that propagate both vertically and horizontally throughout the model, causing convergence issues and model instability. The method of assigning clinker properties that proved to be the most effective and most hydrologically appropriate was to limit the assignment of clinker properties in the model to those clinker bodies on valley margins that are saturated and laterally continuous between coal and alluvium zones (Figure 3-4). Zones delineated as clinker in the model were assigned a range of K between 1000 ft/day and 1500 ft/day (Table 3-3). These values are near the low end of the K range expected for clinker; however, they still adequately represent physical clinker deposits because they provide a non-limiting conduit between coal and alluvium zones in the model.

Layer 2 Areal Properties

The areal properties assigned to Layer 2 are representative of two different conditions that reflect the presence or absence of interburden in the physical Knobloch coal reserve. Parameter assignment in Layer 2 is dependent on position relative to the mapped extent of separation in the Knobloch coal seam. The line of separation used in the model is shown in Figure 3-5. South of the separation line, Layer 2 properties are largely

characteristic of the low permeability interburden between upper and lower Knobloch coal seams. K of interburden zones in the south half of Layer 2 ranged from North of the separation line, Layer 2 parameter zonation is similar to Layer 1 in that properties are typical of Knobloch coal. Properties in both the northern and southern halves of layer 2 were assigned values consistent with clinker or alluvium where appropriate. Note that the thickness of Layer 2 is limited to approximately three feet in the north half of the model. A summary of Layer 2 parameter zonation is included in Table 3-4, attached. Zones listed in the table are illustrated in Figure 3-5.

Layer 3 Areal Properties

The parameter zonation of Layer 3 is illustrated in Figure 3-6 and summarized in Table 3-5 (attached). Areal properties in this layer are representative of the lower Knobloch coal south of the Knobloch coal separation line, as previously described in the discussion of layer 2 properties. In the north half of the model, this layer is predominately characteristic of Knobloch coal underburden and is approximately three feet thick. Where applicable, clinker and/or alluvium properties were also assigned to zones within this layer.

Layer 4 Areal Properties

Layer 4 was uniformly assigned properties consistent with interbedded sandstone/siltstone/shale bedrock of the Fort Union Formation (Figure 3-7): $K = 0.005$ ft/day; $S_s = 1 \times 10^{-6}$ ft⁻¹; $S_y = 0.1$; and anisotropy ratio = 10:1 horizontal to vertical K.

Layer 5 Areal Properties

Layer 5 was uniformly assigned properties consistent with low permeability siltstone or shale bedrock (Figure 3-8): $K = 2.83 \times 10^{-6}$ ft/day; $S_s = 1 \times 10^{-8}$ ft⁻¹; $S_y = 0.005$; and anisotropy ratio = 10:1 horizontal to vertical K.

Layer 6 Areal Properties

Parameters assigned to Layer 6 were based on aquifer test results conducted on wells completed in either the Flowers-Goodale coal or the first sandstone underburden hydrostratigraphic unit beneath the Knobloch coal. This layer was generally divided into

two parameter zones that coincided with the Knobloch coal separation line. South of the separation line, a K of 0.33 ft/day was assigned to the layer. North of the separation line, a K of 2 ft/day was used. The highest K estimated for the Flowers-Goodale coal was in the north half of the model at well B6-U (K = 4.9 ft/day). The storage coefficient and specific yield assigned to this layer were 2×10^{-5} and 0.12, respectively. These storage parameter values are meant to be representative of a composite coal and sandstone aquifer. Parameter zonation for Layer 6 is shown in Figure 3-9.

Layer 7 Areal Properties

Layer 7 was uniformly assigned properties consistent with low permeability siltstone or shale bedrock (Figure 3-10): K = 2.83×10^{-6} ft/day; Ss = 1×10^{-8} ft⁻¹; Sy = 0.005; and anisotropy ratio = 10:1 horizontal to vertical K.

Layers 8 and 9 Areal Properties

Layers 8 and 9 can be considered as one continuous layer and are representative of the lower productive sandstone aquifer encountered during the baseline study. Parameter zonation is the same for both layers and is presented in Figure 3-11. Horizontal K assigned to these layers ranged from 0.1 to 0.2 ft/day; and a vertical anisotropy of 10 (vertical K is 10% of horizontal K) was assumed. A specific storage value of 2×10^{-5} ft⁻¹ and specific yield value of 0.2 were uniformly applied to both layers.

3.5 BOUNDARY CONDITIONS

For all layers, model boundaries were represented by one of three boundary conditions: 1.) no flow; 2.) general head boundaries (GHB); or 3.) river boundaries. The River Package was used to simulate the Tongue River on the western model boundary of all layers; the use of this package is detailed in Section 3.6 below. No flow boundary conditions are appropriate where the direction of groundwater flow is perpendicular to the boundary on baseline potentiometric maps and flow directions at the boundaries are not expected to vary appreciably under simulated stresses. No flow boundaries may also be appropriate to represent boundaries that do not contribute appreciable flow to the model due to low permeability. No flow boundary conditions do not require any model

input. The GHB package is used at model boundaries where flow into or out of boundary cells is required but the source of the flow is distant from the specified boundary. Flow through a GHB is proportional to the head at an external source and the head in the boundary cell (McDonald and Harbaugh, 1988). A conductance slope factor governs the rate of groundwater flow at the boundary and is calculated based on the average hydraulic conductivity of the aquifer material separating the external source/sink from the model boundary and the distance from the external source/sink.

The GHB equation is (McDonald and Harbaugh, 1988):

$$Q_{boundary} = C_{boundary}(H_{source} - H_{cell})$$

Where: $Q_{boundary}$ = flow through the boundary (ft³/day)

$C_{boundary}$ = GHB conductance (ft²/day)

H_{source} = head at the external source (ft)

H_{cell} = head at boundary cell (ft)

Head at the external source may be established by reviewing regional potentiometric surface maps. In the absence of water level data outside the model domain, head at the external source is commonly estimated by projecting the gradient from a known groundwater elevation (head) within the model to a distant point outside of the model. Head at the external source can be lower or greater than head at the model boundary. In the form of the GHB equation presented above, conductance is dimensionally equivalent to transmissivity (i.e. ft²/day). However, MODFLOW input required by the GMS 10.0 user interface requires dimensions of ft²/day/ft. To attain the appropriate dimensions, representative hydraulic conductivity (ft/day) is multiplied by layer thickness (ft) and divided by the distance from the model boundary to the external head (ft). The distance to the external source head is defined by the user. Formulae used to estimate conductance and external source head are as follows.

Conductance:

$$C = \frac{K * b}{L}$$

where:

C = conductance (ft²/day/(ft))

K = hydraulic conductivity (ft)

b = layer thickness (ft)

L = distance from boundary to reference head (ft)

Head at external source:

$$H_{ext} = H_{in} + i * L$$

where:

H_{ext} = head at external source (ft)

H_{in} = Head at known point in model (ft)

i = hydraulic gradient (ft/ft)

L = distance from H_{in} to H_{ext} (ft)

Calculations of GHB conductance and external source head were performed for GHB in all layers to evaluate a range of appropriate values based on variability in physical properties (i.e. hydraulic conductivity, saturated thickness, and gradient) that may be present at the model boundary. Values were varied during the model development process to obtain a GHB parameter set that promoted numerical stability and produced a reasonable representation of flow conditions. GHB parameters were further refined in the model calibration process. A discussion of boundaries used in all nine model layers, including GHB parameters used in the final calibrated model, are discussed herein.

Layer 1 Boundary Conditions

The assignment of boundary conditions in Layer 1 is presented in Figure 3-4. GHB conditions were applied along the northern edge of the model including sections of the boundary perpendicular to and in contact with Tongue River, Otter Creek, and East Fork Otter Creek alluvium. The Tongue River and Otter Creek alluvium GHB were assigned flow out conditions; while the East Fork Otter Creek GHB was assigned conditions that would result in flow into the model. Other GHB assigned to Layer 1 include: the entire east edge of the model layer; the south edge of Layer 1 from the southwest corner to Otter Creek; Otter Creek alluvium at the south end of the model domain (inflow); and Tongue River alluvium in the southwest corner of the model domain (inflow). A range of GHB parameters was calculated for each boundary based on the range of possible K and model layer thicknesses (Table 3-6). GHB parameters were tested by trial and error during the model development and calibration processes to attain final values that

resulted in an agreeable estimate of flow direction and budget at the boundaries. Conductance values assigned to the north and south boundaries were assigned decreased conductance values, as compared to the east boundary, because flow through these boundaries is tangential to the primary direction of groundwater flow. Also, GHB conductance was assigned conservative values at these boundaries so as not to affect drawdown predictions in transient model simulations.

Final GHB parameters used in the model for each boundary are included in Figure 3-4. Boundaries are assigned alphabetic identifiers that are consistent between Table 3-6 and Figure 3-4. External source heads were estimated by projecting established hydraulic gradients from representative water levels at points nearest to or in the direct flow path of a given GHB. For example, head at well A9 was used to estimate the external head for the boundary. Well A9 is approximately 5,000 feet downgradient from GHB D (shown in Figure 3-4 and in Table 3-6 as Otter Creek/Tongue River alluvium outflow). Other wells or points used in Layer 1 GHB parameterization are identified in Table 3-6.

TABLE 3-6. LAYER 1 GHB PARAMETER CALCULATIONS

LAYER 1 GHB Conductance Estimation									LAYER 1 GHB External Source Head Estimation							
$C = K*b/L$									$H_{ext} = H_{in} \pm i * L$							
Boundary Description	Hydraulic Conductivity, K (ft/day)		Layer Thickness, b (ft)		Distance, L (ft)	Conductance, C (ft ² /day/(ft))			Well/Point	H _{in} (ft)	i (ft/ft)		L (ft) *	H _{ext} (ft)		
	min	max				min	max	final			min	max		min	max	final
A. Otter Creek Alluvium In	3.4	554	--	40	10000	0.014	2.2	0.25	WO-8	3141	0.002	0.005	17400	3176	3228	3210
B. Tongue River Alluvium In	3.4	554	--	34.5	10000	0.012	1.9	0.6	183560	3027	0.002	0.005	36500	3100	3210	3120
C. East Fork Otter Creek In	3.4	554	--	42	10000	0.014	2.3	0.13	AVF1-3	2971	0.007	0.009	39000	3244	3322	3290
D. Otter Creek/Tongue River Alluvium Out	3.4	554	--	43	10000	0.015	2.4	0.19	A9	2925.23	0.002	0.005	15000	2850	2895	2858 - 2880
E. East Boundary	0.1	10	35	56	10000	0.00035	0.1	0.05	B6-K	3108.05	0.005	0.01	62800	3422	3736	3650 - 3668
F. North Boundary	0.1	10	33	35	10000	0.00033	0.035	0.00075	B6-K	3108.05	0.005	0.01	45000	3333	3558	3400
G. South Boundary	0.1	10	33	35	10000	0.00033	0.035	0.00075	B-7KU	3144	0.005	0.01	37720	3333	3521	3400

*L is length from known point to boundary plus 10,000 feet to external reference head.

Layer 2 Boundary Conditions

No flow boundaries were assigned to the entire perimeter of Layer 2, since there is no significant inflow component to the model from the lower permeability interburden. The only exceptions were in the vicinity of the Tongue River/Otter Creek. GHB boundaries were used in Layer 2 to represent the Tongue River alluvium inflow component in the

southwest model corner and the Tongue River/Otter Creek alluvium outflow section in the northwest corner of the model. These boundaries are mapped in Figure 3-5. GHB parameterization for Layer 2 is presented in Table 3-7. As described above, final values of GHB parameters assigned to this layer were determined by trial and error during the numerical model development and calibration process until flow direction and magnitude were in agreement with the conceptual model.

TABLE 3-7. LAYER 2 GHB PARAMETER CALCULATIONS

LAYER 2 GHB Conductance Estimation									LAYER 2 GHB External Source Head Estimation							
Boundary Description	Hydraulic Conductivity, K (ft/day)		Layer Thickness, b (ft)		Distance, L (ft)	Conductance, C (ft ² /day/(ft))			Well/Point	H _{in} (ft)	i (ft/ft)		L (ft) *	H _{ext} (ft)		
	min	max				min	max	final			min	max		min	max	final
	A. Tongue River Alluvium In	3.4	554	--	20	10000	0.0068	1.108	0.5	183560	3027	0.002	0.005	36500	3100	3210
B. East Fork Otter Creek In	3.4	554	--	2.5	10000	0.00085	0.1385	0.06	AVF1-3	2971	0.007	0.009	39000	3244	3322	3290
C. Otter Creek/Tongue River Alluvium Out	3.4	554	--	2.5	10000	0.0009	0.14	0.06	A9	2925.23	0.002	0.005	15000	2850	2895	2858 - 2880

*L is length from known point to boundary plus 10,000 feet to external reference head.

Layer 3 Boundary Conditions

The northern half of model Layer 3 is very thin and is assigned low hydraulic parameters consistent with underburden bedrock. As such, the north and northeast boundaries of Layer 3 are assigned no flow conditions. In the southern half of the numerical model this layer is used to represent the Lower Knobloch Coal; thus, it has an inflow component represented by GHB conditions. Three alluvial boundaries are present in Layer 3 that are also simulated by GHB conditions. The Layer 3 boundary condition assignment is included in Figure 3-6; and GHB estimates are summarized in Table 3-8. As described above, final values of GHB parameters assigned to this layer were determined by trial and error during the numerical model development and calibration process until flow direction and magnitude were in agreement with the conceptual model.

TABLE 3-8. LAYER 3 GHB PARAMETER CALCULATIONS

LAYER 3 GHB Parameter Estimation									LAYER 3 GHB External Source Head Estimation							
$C = K \cdot b / L$									$H_{ext} = H_{in} + i \cdot L$							
Boundary Description	Hydraulic Conductivity, K (ft/day)		Layer Thickness, b (ft)		Distance, L (ft)	Conductance, C (ft ² /day/(ft))			Well/Point	H _{in} (ft)	i (ft/ft)		L (ft) *	H _{ext} (ft)		
	min	max				min	max	final			min	max		min	max	final
A. East Fork Otter Creek In	3.4	554	--	2.5	10000	0.00085	0.1385	0.06	AVF1-3	2971	0.007	0.009	39000	3244	3322	3290
B. Otter Creek/Tongue River Alluvium Out	3.4	554	--	2.5	10000	0.0009	0.14	0.06	A9	2925.23	0.002	0.005	15000	2850	2895	2858 - 2880
E. East Boundary	0.1	10	35	56	10000	0.00035	0.1	0.01	B6-K	3108.05	0.005	0.01	62800	3422	3736	3650 - 3668
F. South Boundary	0.1	10	33	35	10000	0.00033	0.035	0.00075	B-7KU	3144	0.005	0.01	37720	3333	3521	3400

*L is length from known point to boundary plus 10,000 feet to external reference head.

Layer 4 Boundary Conditions

Except for the River boundary on the west side of the model, the entire perimeter of Layer 4 is assigned a no flow boundary condition (Figure 3-7) since there is no evidence of a significant flow component from the low permeability underburden.

Layer 5 Boundary Conditions

Except for the River boundary on the west side of the model, the entire perimeter of Layer 5, which represents low permeability shale bedrock, is assigned a no flow boundary condition (Figure 3-8).

Layer 6 Boundary Conditions

Model boundaries assigned to Layer 6, the Flowers-Goodale coal or first sandstone underburden, are presented in Figure 3-9. The GHB in Layer 6 were parameterized as shown in Table 3-9. GHB were assigned in this layer to the east and south sides of the model.

TABLE 3-9. LAYER 6 GHB PARAMETER CALCULATIONS

LAYER 6 GHB Parameter Estimation								LAYER 6 GHB External Source Head Estimation								
$C = K*b/L$								$H_{ext} = H_{in} + i * L$								
Boundary Description	Hydraulic Conductivity, K (ft/day)		Layer Thickness, b (ft)		Distance, L (ft)	Conductance, C (ft ² /day/(ft))			Well/Point	H _{in} (ft)	i (ft/ft)		L (ft) *	H _{ext} (ft)		
	min	max				min	max	final			min	max		min	max	final
A. East Boundary - North	0.014	5	27	50	10000	0.00004	0.025	0.00025	B4-U	3059.1	0.002	0.005	70720	3201	3413	3220-3240
B. East Boundary --South	0.014	5	27	50	10000	0.00004	0.025	0.00075	224810	3172	0.002	0.005	46960	3266	3407	3240-3275
C. South Boundary --East	0.014	5	27	50	10000	0.00004	0.025	0.00075	WO-5	3143	0.002	0.005	17920	3179	3233	3225
D. South Boundary - West	0.014	5	27	50	10000	0.00004	0.025	0.00025	--	--	--	--	--	--	--	3065

*L is length from known point to boundary plus 10,000 feet to external reference head.

Note that relatively low values of GHB conductance were assigned at the model boundaries compared to K values assigned in the model. As described above, final values of GHB parameters assigned to this layer were determined by trial and error during the numerical model development and calibration process until flow direction and magnitude were in agreement with the conceptual model. Higher values of GHB conductance assigned during model development resulted in an overestimate of head and flux in model layer 6. The source of extra water in this layer is flow through the upper face of Layer 6 cells from overlaying layers. GHB parameters assigned to this layer may result in a low estimated flux at the model boundary but provide a more accurate account of heads and flux immediately beneath the simulated Tract 2 mine area. Flux in Layer 6 is discussed further in Section 4.4 to follow.

Layer 7 Boundary Conditions

No flow boundary conditions were used around the perimeter of this layer, which represents low permeability shale bedrock, except for the river boundary on the western edge (Figure 3-10).

Layers 8 and 9 Boundary Conditions

Boundary conditions for Layers 8 and 9 were parameterized identically: No-flow boundary conditions were applied along the northern edge of the model; the River Package was assigned along the west boundary; and GHB were applied along the east

and south sides of the model (Figure 3-11). GHB parameters were estimated as shown in Table 3-10.

TABLE 3-10. LAYERS 8 AND 9 GHB PARAMETER CALCULATIONS

LAYER 8 (and 9) GHB Parameter Estimation								LAYER 8 (and 9) GHB External Source Head Estimation								
$C = K*b/L$								$H_{ext} = H_{in} + i * L$								
Boundary Description	Hydraulic Conductivity, K (ft/day)		Layer Thickness**, b (ft)		Distance, L (ft)	Conductance, C (ft ² /day/(ft))			Well/ Point	H _{in} (ft)	i (ft/ft)		L (ft) *	H _{ext} (ft)		
	min	max				min	max	final			min	max		min	max	final
A. East Boundary	0.014	5	50	70	10000	0.00007	0.035	0.0025 - 0.005	B5-U	3066	0.002	0.005	70720	3207	3420	3195 - 3280
B. South Boundary --East	0.014	5	50	70	10000	0.00007	0.035	0.00025	B10-U	3114	0.002	0.005	26400	3167	3246	3220
C. South Boundary - West	0.014	5	50	70	10000	0.00007	0.035	0.00025	--	--	--	--	--	--	--	3100

*L is length from known point to boundary plus 10,000 feet to external reference head.

**Thickness is cumulative thickness of layers 8 and 9.

GHB parameters were estimated by trial and error in the model development process and were chosen based on the closest output of potentiometric head in this layer. Calibration to observed head and flux in Layer 8 is discussed in Section 4.0.

3.6 RIVER PACKAGE

The River Package is analogous to the GHB package in that flow into or out of river cells is proportional to the difference in head between the assigned river head and head in adjacent cells. The factor of proportionality is known as the river conductance. River conductance is the product of the vertical hydraulic conductivity of the riverbed and the width of the stream bed as it crosses the cell -- divided by the thickness of the streambed material (McDonald and Harbaugh, 1988). The River Package was used to simulate three surface water features (Tongue River, Otter Creek, and Pond P6) in the numerical model. Each is discussed specifically in the following sections.

3.6.1 Otter Creek

The River Package was used in the model to represent Otter Creek. The package was assigned to Layers 1 through 3 in the south half of the model where Layers 1 through 3 represent the separated Knobloch coal sequence that sub-crops in the alluvium of Otter Creek. The River Package assignment was limited to Layer 1 in the north half of the model.

The river conductance assigned to the Otter Creek River Package was 2.5 (ft²/day)/ft. As with the Tongue River conductance, this parameter can be expected to be highly variable based on river bed thickness and sediment composition. River beds of clinker or gravel composition would have high vertical K and promote interaction between surface water and groundwater. Conversely, fine-grained (clayey) sediments would limit conductance through the streambed. Conductance of the Otter Creek streambed was tested informally during several pumping tests performed at alluvial wells in proximity to the creek. Typically, drawdown in the pumping wells was not inhibited by recharge from the creek. This observation indicates that the conductance between the creek and the alluvial aquifer is limited.

The relationship between streambed elevations and alluvial groundwater levels is critical to calculation of gaining or losing conditions in the stream. Streambed elevations consistent with those surveyed at surface water monitoring sites and/or interpreted from USGS topographic maps were input at river nodes and extrapolated to the entire model reach. Surface water gage heights representative of baseflow conditions were used in steady state and transient simulations. Nodes with streambed and head stage elevations used in the Otter Creek river package are presented in Figure 3-12.

3.6.2 Tongue River

As noted above, the River Package was used to represent the Tongue River and provide a hydrologic boundary condition in all layers on the west edge of the model. The river is spatially accurate in its position relative to other model features; however, some sinuosity was removed from the modeled river to simplify the boundary. River elevations assigned to this boundary in the River Package were consistent with river bed elevations interpreted from USGS topographic maps. Specifically, elevations were assigned to river nodes where contour lines crossed the riverbed. Head in the river was assumed to be 1.5 to three feet above the riverbed. Nodes with riverbed and head assignments are shown in Figure 3-12. A river conductance of 100 (ft²/day)/ft was assigned to the Tongue River Boundary. This conductance is consistent with a river width of 100 feet, a vertical K of 1 ft/day, and a bed thickness of 1 ft. The actual K and riverbed thickness are uncertain

and are likely to vary throughout the modeled reach. Fine grained river bed sediments, such as those observed in Otter Creek, are also expected in the Tongue River; however, the river is known to gain substantially in the reach considered in the model. River conductance at this boundary was assigned a value that would be characteristic of the fine grained sediments but not limiting to potential groundwater/surface water interaction.

3.6.3 Pond P6

The River Package was applied to four grid cells in the Tenmile Creek drainage to represent Pond P6. Head in the pond was assigned a value of 3163 feet, based on measured water levels in fall months of the baseline study. Consistent with the Otter Creek river package, a river conductance of 2.5 (ft²/day)/ft was assigned to the pond. The Pond P6 river package is shown in Figure 3-12.

3.7 RECHARGE PACKAGE

In MODFLOW, recharge is only applied to the uppermost active model layer (Layer 1). Recharge values consistent with those previously presented in Section 2.1.2 were distributed over the model domain as illustrated in Figure 3-13. As noted, recharge rates vary with surface geology in the physical system. Recharge areas assigned to the model were largely consistent with zones of hydrogeologic parameters previously assigned to Layer 1 to represent coal, clinker, or alluvium. Some polygons were assigned values of recharge that were increased above those that would typically be assigned for a given set of hydrogeologic properties. This was done for one of two reasons: to simulate instances where unsaturated clinker may be present in the surface geology directly overlaying the saturated coal aquifer; or to account for shortfalls in the flow budgets of tributary drainages that were cut off where not in contact with the Knobloch coal.

3.8 ZONE BUDGETS

Zone budgets were delineated in both the steady-state and transient models to quickly identify and output flow components from key features in the model domain. Zone budgets are identified in Figure 3-14 and are described here.

- Zone 1 – This zone represents the upstream reach of Otter Creek from Fifteenmile Creek to Tenmile Creek (Reach 1). This reach is not gaged and output from this zone in the steady-state model was not considered in the calibration phase of numerical model development. However, flow budgets from this zone were used to evaluate potential mine influences on surface water groundwater interaction upstream of the mine.
- Zone 2 – This zone represents Reach 2 of Otter Creek from Tenmile Creek to surface water site SW-16. Steady-state budgets from the River Package were compared to observed flows in this reach during model calibration and transient model budgets from Zone 2 (Reach 2) were used to assess changes in stream gains/losses during the mine simulation.
- Zone 3 – Reach 3 of Otter Creek from SW-16 to USGS gaging station 06307740 is assigned to Zone 3. This reach of Otter Creek is downstream of the mine. The steady state model was expressly calibrated to observed stream flow gains in this reach; and transient model budgets from Zone 3 were used to evaluate potential changes in groundwater-surface water interactions as a result of mining activities and to quantify potential depletion effects on Otter Creek downstream of the mine.
- Zone 4 – The purpose of Zone 4 was to quantify gains to the Tongue River simulated in the steady state model by the River Package. Effectively simulating the gaining flow in this reach was one of the model calibration objectives.
- Zone 5 – The mine area flow budget was assigned to Zone 5. Model flow budgets output from this zone were instrumental in evaluation of steady state and transient simulations. The steady state budget through this zone was compared to Darcy's flux estimates for the Knobloch coal during the calibration phase of model development. In transient simulations, this zone was used to quantify mine dewatering rates by evaluating flow to drains. Finally, the relationship of flow from Zone 6, described below, to Zone 5 was used to identify lateral recharge patterns during and after mining.
- Zone 6 – The proposed Otter Creek Mine plan specifies that a 500 foot coal buffer will be left in place on the east side of the mine between Otter Creek alluvium

and/or clinker deposits. This buffer is assigned to Zone 6. The baseline groundwater flow direction is generally from the mine area to the coal buffer. As mine dewatering progresses, and for some years after mining, the flow direction is expected to shift such that groundwater will flow from the alluvium through the buffer zone. The timing and magnitude of the shift in flow direction was evaluated by comparing Zone 5 and 6 flow budgets throughout the simulated period of mine development and in the post-mine flow system.

- Zones 7 through 9 – These zones represent the downgradient flow path of groundwater from the coal buffer zone. Each of these zones was delineated based on particle tracking analysis conducted via post-mine water level recovery simulations. Transient simulations and the use of particle tracking are discussed in further sections of this report.

Model flow budgets used in evaluation of steady state or transient conditions were not limited to the six zones specified above. The GMS user interface makes it easy to access the flow budget for any cell, group of cells, or boundary arc.

3.9 TRANSIENT MODEL (MINE DEWATERING SIMULATION)

Mine dewatering was simulated in transient model runs to evaluate groundwater inflow and dewatering rates to open mine cuts, assess changes in groundwater levels (drawdown) due to mining in principal aquifers surrounding the mine area, evaluate potential changes in surface water/groundwater interaction, and estimate post mine water level recovery rates, as specified in model objectives three through six. Transient mine dewatering simulations were initiated using the numerical model parameterization discussed above; however, several key considerations were made in the development of transient simulations that require additional discussion and parameter identification.

- The Drain Package was added to the model to simulate dewatering the proposed mine cuts. Drains were turned on and off in a sequence meant to approximate the mine plan.
- Aquifer properties were changed from those representative of coal to those representative of spoils in the backfilled cuts as the mine dewatering simulation progressed.

- Recharge rates were kept constant in the spoils to provide conservative estimates of drawdown and budget depletion outside of the mine area.
- Because MODFLOW does not allow for the transient assignment of hydrologic properties (e.g. K, specific storage, anisotropy), the transient evaluation had to be conducted in a series of successive (cascading) model runs.
- Stress periods were assigned to the model consistent with timing specified in the proposed 19-year Tract 2 mine sequence. Longer stress periods were applied to a simulated 500-year period of post-mine water level recovery.

3.9.1 Drain Package

Mine dewatering was simulated by use of the Drain Package, applied to polygons designated as mine cuts in model Layer 1 (Figure 3-15). The simulation of dewatering by drains produces a more rapid response than actual dewatering pumps; but the simulation by drains greatly simplifies the numerical model and is expected to produce a conservative dewatering budget.

Drains are simulated in MODFLOW by applying a drain conductance and elevation. The drain conductance is a slope factor that controls the rate at which water issues to the drain. Flow simulation by the Drain Package is similar to the River Package in that flow is proportional to head in adjacent cells; the exception is that flow cannot issue from drains (McDonald and Harbaugh, 1988). When head surrounding a drain is equal to or lower than the drain elevation, no flow issues to the drain. For polygons, drain conductance is entered into GMS, and later assigned to MODFLOW on the basis of conductance per unit area. Thus, drain conductance takes the form:

$$C_{drain} = \frac{\frac{k}{b}lw}{A} = K/b$$

Where: k = hydraulic conductivity (ft/day)

b = saturated layer thickness (ft)

l w= cross sectional area perpendicular to flow (ft²)

A = area of drain polygon (ft²)

GMS converts the stress from a polygon to a MODFLOW grid cell; in doing so, the interface automatically multiplies the entered value of conductance by the cell dimensions covered by the polygon to create an appropriate conductance value. (Aquaveo, 2014). Based on an average mine area K of 3.6 ft/day and a coal layer thickness of 70 ft, conductance calculated for a 500 ft x 500 ft drain cell would be 0.0072 (ft²/day)/ft². A conductance value of 0.04 day⁻¹ ((ft²/day)/ft²) was assigned to the model so as not to introduce drain inefficiencies that would limit dewatering rates.

Drain elevations were based on layer structure contours, which were generated from coal bottom elevations determined during monitoring well and exploration drilling. As such, drain elevations were variable throughout the mine area. Drain elevations were established so that the cells would be dewatered to near their bottom depths but not completely dried. Cells were not allowed to dewater completely in the model because dry cells often cause numerical instability. Drain elevations assigned to mine polygons are presented in Figure 3-15.

Drains were activated and de-activated in a sequence that closely follows the proposed mine plan. The sequence is shown in Figure 3-15; and the drain activation routine is discussed further in Section 3.9.3.

3.9.2 Coal to Spoils Aquifer Properties

Aquifer properties in the mine area of Layer 1 were changed from parameters representative of a coal aquifer to parameters representative of a spoils aquifer as the mine cuts are backfilled. Coal properties assigned to the mine area were discussed previously and are presented in Figure 3-4. Spoils properties assigned to mine area polygons shown in Figure 3-15 are: $K = 0.25$ ft/day; $S_y = 0.12$; $S_s = 2 \times 10^{-5}$; and anisotropy ratio = 1. Recharge rates were kept constant in the spoils to provide conservative estimates of drawdown and budget depletion outside of the mine area.

3.9.3 Cascading Models and Transient Stress Periods

Because MODFLOW does not allow for the transient assignment of hydrologic properties (e.g. K, specific storage, anisotropy), the transient evaluation had to be conducted in a series of 11 successive model runs to simulate the progressive backfilling of mine cuts with spoils. Each of the first nine model runs was used to simulate two years of mine dewatering. The tenth model run simulated 180 days of dewatering from the final two mine polygons in year 19. The eleventh and final model run simulated 100 years of water level recovery in the post-mine environment. Successive (cascading) model simulations were executed according to the general procedure and stress periods as follows:

- Years 1 and 2 – Mine cuts are to be made by mobile equipment in the first two years of mining. Mobile equipment pits are divided into smaller drain polygons, each representing one month of mining (Figure 3-15). Each drain polygon is activated for a single stress period in the simulation; thus, the first two years of simulation were conducted using 24 stress periods of equal 30-day duration. Stress periods were further divided into three 10 day time steps and model output was generated for each time step. Head output for the final time step was imported into the next successive transient model run (for years three and four). Drains used to simulate dewatering in the first two years were turned off; and areal properties of the deactivated drain polygons were changed from coal to spoils.
- Years 3 through 19 – After year two, drains were activated over the remaining life of mine in eight successive 90-day stress periods for each of the two-year cascading model runs. The final year of the transient runs (year 19) was simulated in two 90-day stress periods, one stress period for each of two drain polygons. Each of the 90-day stress periods in years 3 through 19 contained three 30-day time steps and model output was generated for each time step. As above, head output for the final time step of each simulation was imported into the next successive transient model run. Drains used to simulate dewatering in each run were turned off; and areal properties of the deactivated drain polygons were

changed from coal to spoils. Drain polygons used in these stress periods were made larger than those activated in the first two years of the transient simulation. Each drain polygon represents about one quarter-year of mining. Results of the transient simulation indicate that the increased drain size had little effect on simulated dewatering rates or water level drawdown, when compared to the more finely divided drain polygons.

- Post-mine (500 years) – Heads output from the last time step of the final mine dewatering simulation (year 19) were used as starting heads for the post-mine water level recovery simulation. All drain stresses were deactivated in this simulation; and hydrologic properties of the final two mine polygons were changed from coal properties to spoils properties. Stress periods of one year (365 days) were applied to each of the first ten years of the post-mine simulation. Years 10 through 50 were simulated via eight five-year (1,825 days) stress periods; and finally, years 50 to 500 were simulated via forty-five 10-year (3,650 days) stress periods. Each post-mine stress period was conducted as a single time step and model results were output at the end of each stress period.

MODPATH was used to apply particle tracking to the perimeter of the mine area at the beginning of the post-mine simulation. Particle pathways were mapped to illustrate post-mine flow patterns. Specifically, the flow paths were used to delineate zone budgets for downgradient units between the mine and Otter Creek. In addition to augmenting the analysis of post-mine recovery rates, flow budgets/pathways were used in the evaluation of potential spoils water quality impacts downgradient of the mine. Water quality evaluation is included in Section 6 of Exhibit 314C, Probable Hydrologic Consequences.

Drawdown was calculated at the end of each of the two-year mine dewatering simulations, at the end of the year 19 dewatering simulation, and every five years during the post-mine recovery simulation until drawdown reached a level less than five feet. All drawdown was calculated relative to the starting head used in the first dewatering simulation (year 1), from the calibrated steady state model.

4.0 STEADY-STATE SIMULATION AND MODEL CALIBRATION

Numerical model development and the calibration process is an iterative progression that requires varying input parameters within a range of practical values until the model output closely approximates gathered field observations and data. A trial and error approach was used to calibrate the Otter Creek groundwater flow model; whereby, hydrologic parameter inputs including hydraulic conductivity, river conductance, recharge rates, general head conductance, and general head external source elevations were varied until an acceptable level of model error was reached. Statistical measures of model fit were chosen prior to beginning the calibration process. The Otter Creek groundwater flow model was calibrated to three separate steady-state conditions: 1.) calibration to observed head; 2.) calibration to stream losing and gaining reaches in Otter Creek and the Tongue River; and 3.) calibration to flux through, coal, alluvium, and underburden. Calibration to observed head was the primary calibration objective because validated water level measurements are much more precise than either stream flow measurements or groundwater flux estimates. As a qualitative measure of the steady state calibration, the simulated steady state potentiometric surfaces for aquifer model layers were compared to previously interpolated potentiometric surfaces.

Successful development of a calibrated steady-state flow model is implied in Objectives 1 and 2 of the modeling process. The calibration process and attainment of these objectives are detailed herein.

4.1 FLOW BUDGET

The flow budget for the steady-state calibrated model is presented in Table 4-1. As outlined in the development of the numerical model, sources of flow into the model are river leakage, GHB, and recharge. Flow out of the model is in the form of either GHB outflows or river leakage. The total budget in the model is 1981631cfd, or approximately 23 cfs. The calculated discrepancy between flow in and flow out of the model is -0.105 cfd, which equates to a minute percent difference of -5.3×10^{-6} .

TABLE 4-1. STEADY STATE FLOW BUDGET

Sources/Sinks	Flow In	Flow Out	Flow In	Flow Out	Flow In	Flow Out
	ft ³ /day	ft ³ /day	cfs	cfs	gpm	gpm
CONSTANT HEAD	0	0	0	0	0	0
RIVER LEAKAGE	1351553.79	1874315.64	15.64	-21.69	7020.57	-9736.03
HEAD DEP BOUNDS	206346.88	-107315.52	2.39	-1.24	1071.86	-557.44
RECHARGE	423730.38	0	4.90	0.00	2201.04	0.00
Total Source/Sink	1981631.06	1981631.17	22.94	-22.94	10293.47	-10293.47
			0.00	0.00	0.00	0.00
TOTAL FLOW	1981631.06	1981631.17	22.94	-22.94	10293.47	-10293.47
Summary	In - Out	% difference	In - Out	% difference	In - Out	% difference
Sources/Sinks	-0.105	-5.30E-06	-0.105	-5.30E-06	-0.105	-5.30E-06
Cell To Cell	0	0	0	0	0	0
Total	-0.105	-5.30E-06	-0.105	-5.30E-06	-0.105	-5.30E-06

*Note: MODFLOW output is in units of cubic feet per day (cfd). Units converted for more appropriate dimensional comparison. Negative river leakage represents flow to the River package, or a net gain in stream flow. Positive river leakage represents flow to the model from the river, or a net loss in stream flow.

4.2 CALIBRATION TO WATER LEVEL OBSERVATIONS

Calibration to observed head was the primary calibration objective of the Otter Creek groundwater flow model. Static water levels from 81 wells, including monitoring wells in the Otter Creek baseline study area and several private wells, were used to calibrate the model to steady-state potentiometric head. The goal of model calibration to observed head is to minimize residuals between observed and calculated heads. The highest degree of calibration is known as Level 1 calibration. A Level 1 calibration results when the simulated head at a given well is within a predetermined target value of the observed head (Anderson and Woessner, 1991). Residuals acceptable to attainment of Level 1 calibration in this modeling effort were stratified based on the hydrologic unit of completion, proximity to the area of applied stress (mine area), and uncertainty in water

level data of each calibration target. Water levels used as calibration targets and targeted residuals for each are presented in Table 4-2.

In general, residual targets were established as follows:

- Calibration targets in Otter Creek alluvium of Layer 1 were assigned a target residual of ± 5 feet.
- Calibration targets in the mine area of Layer 1 were assigned a residual target of ± 10 feet.
- All other calibration targets in Layer 1 that were derived from data collected during the baseline study were assigned a target residual of ± 15 feet.
- Wells completed during the baseline study in layers 3, 6, or 8 were assigned target residuals of ± 15 feet.
- Calibration targets derived from public sources (i.e. GWIC) were assigned residual targets of ± 30 feet in all layers. The higher residual targets established for these sites reflects measurement error that is possible in either the initial survey or estimate of well measuring point elevation and/or potential error in the method used to measure the actual static water level. The quality of GWIC data used in the model varies. For sites with surveyed datum and published hydrographs, measurement error is expected to be less; but sites with data estimated from driller's well logs might easily have a margin of ± 30 feet of error.

A common method of determining targeted residuals is to assume an acceptable level of error equal to 10 percent of the change in head observed in the model domain. By this method, simple models with a relatively gradual potentiometric surface are allowed less error than complex flow models with large changes in head. If this method were applied to water level data used in the calibration of the current model, a residual of approximately ± 28 feet would be acceptable. The residual targets established above for validated baseline data observations require a more stringent level of calibration; however, the ± 30 feet residual target is adequate for certain GWIC data, when the potential for measurement error is considered.

Results of the steady state calibration to observed head are included in Table 4-2. Residual statistics used to quantify calibration of the Otter Creek flow model are included in the table and discussed in detail as follows.

Computed vs. Observed Head – Computed heads were generally in agreement with observed heads used in the calibrated model. Computed water levels at 77 of the 81 calibration points were within the established Level 1 residual target values for head. Only computed heads at wells A2 and B8-KU (Layer 1) and B8-KL and B12-KL (layer 3) were outside the established residual targets. Residual heads at wells A2 and B8-KU were -20.16 and 20.87 feet, respectively. These residuals are within two times the residual target of ± 15 feet. Residuals within two times the acceptable level of error of the prescribed target may be referred to as a Level 2 calibration (Anderson and Woessner, 1991). Well A2 is located near the upstream end of alluvium of the Home Creek drainage considered in the model. There is a lateral hydraulic connection between the Knobloch coal and alluvium at this location in the physical system, possibly through clinker bodies on the drainage margins. The overestimate of head at A2 may be resultant of an under-assignment of clinker in this area of the model. Due to uncertainty in the relationship between clinker, coal, and alluvium in this part of the drainage, residual error at A2 was accepted in the steady state calibration. A more conservative estimate of drawdown in transient simulations will result in this area by not including additional clinker parameters.

Residual heads were the greatest at the B8-KL and B12-KL calibration targets in Layer 3. Error calculated at these targets was -73.70 feet and -34.88 feet, respectively. This level of error is outside of the range of either a level 1 or 2 calibration. The primary source of residual error in Layer 3 is likely the exaggerated hydraulic connection between the simulated upper and lower Knobloch coals (Layers 1 and 3).

As noted, high residual error is present at both Knobloch coal wells used as calibration targets at the B8 battery (B8-KU and B8-KL). The Knobloch coal seams at this battery are separated by just 26 feet of siltstone/shale in the physical system and are represented

as such in the layer structure of the model. However, water level observations considered in the model for wells B8-KU and B8-KL were 3144.94 and 3049.99 feet, respectively. Use of an effective porous media model makes it difficult if not impossible to simulate such a steep vertical hydraulic gradient with the minimal amount of separation, as the model cannot simulate stratigraphic units that have no connectivity. Error at the B8 battery may largely be resultant of the models tendency to exaggerate the hydraulic connection between Layers 1 and 3; but there may be other possible sources of error at the B8 battery that are not well constrained at this time. Other possible sources of error at the B8 battery may include transient effects from a nearby forest service pumping well (GWIC 7589) or a fault that is not well characterized in the current understanding of Otter Creek geology. No faults are currently mapped in this area. Hydrologic conditions at the B8 well battery and the surrounding area will need to be further evaluated during baseline study and analysis of potential mine influences at Tract 3. However, the inability of the current model to accurately predict head at this isolated battery should not be problematic in the overall analysis because an overestimate of the hydrologic connection will result in a conservative estimate of drawdown in the split layers and because these wells are on the opposite side of a major hydrologic boundary (Otter Creek) from the stresses that were applied during transient simulations.

Maximum and Minimum Residual Head – The maximum residual head in the calibrated model was 22.26 feet, calculated at calibration target 176635 (GWIC ID) in layer 8. The maximum residual head was within the level 1 calibration target of ± 30 feet. As previously discussed, minimum residual head, calculated at well B8-KL of Layer 3, was -73.7 feet. The residual target at this well was ± 15 feet. Positive residual head is indicative of an under-prediction of actual head; while, negative residuals are indicative of an over-prediction of head. Positive residuals were calculated at 26 of the 81 calibration targets; while, negative residuals were calculated at 55 of the targets. This indicates that the model on average tends to slightly overestimate initial water level conditions.

Mean Residual Head – Mean residual head in the calibrated model was -2.39 feet. The mean of the residuals does not provide the best stand-alone quantification of model error because negative and positive residuals annul each other during averaging. However, a strongly negative or positive value of mean residual head is indicative of a model's tendency to universally over- or under-predict head. The mean residual head for the Otter Creek model is low but negative, which indicates a slight tendency to over-predict known water levels.

Mean Absolute Residual Head -- The mean of the absolute values of the residuals is often used as the defining statistic of model calibration. Because successive positive and negative values are cumulative rather than deducted, this statistic provides a metric of absolute error. The mean absolute residual head for the calibrated Otter Creek flow model is 7.22 feet.

Cumulative Sum of Squared Residuals – A plot of cumulative sum of squared residuals is included in Figure 4-1. This plot indicates both the relative level of error associated with individual calibration targets and the cumulative model error. Had the absolute residual error been at the extreme upper bound of Level 1 calibration (i.e. all residuals at equal to the residual target values), the cumulative sum of squared residuals would be 31,075. The calculated cumulative sum of squared residuals of 12,238 is less than half of the acceptable value and is well within normal acceptable limits for model calibration.

Standard Deviation – The residual standard deviation of the calibrated model is 12.13. A common measure of calibration is to achieve a value of residual standard deviation that is less than ten percent of the range in observed head (i.e. standard deviation/range in observed head = 0.1). For the Otter Creek model, the standard deviation divided by the range in observed head is equal to approximately four percent (0.04).

Residual Normality and Spatial Analysis

Site-wide calibration statistics such as those presented above are useful for broadly characterizing the degree of model calibration; however, it is also necessary to evaluate

spatial patterns in residuals to identify obvious trends that may influence results at key hydrologic features in the model.

A plot of computed versus observed heads was constructed in attempt to identify trends of over- or under-prediction (Figure 4-2) within the model domain. On such a plot, trends can be identified by plotting computed versus observed head relative to a line of 1:1 slope. If the slope of the observations strays from the line, a trend is evident. Note that computed and observed heads are categorized by layer in the plot. In general, observations in Layer 1 and Layer 6 conform to the line of 1:1 slope. Interpretation of results for Layers 3 and 8 are limited by the low number of observations in these layers. However, heads in layer 3, most notably the residuals at calibration targets B8-KL and B12-KL, stray from the line indicating the over-prediction of head discussed above. A plot of residual versus observed heads is included in Figure 4-3. Heads in the plot are categorized by layer; and implications of this plot are similar to that of the plot of computed versus observed heads. A discussion of residuals for each of the model aquifer layers is included as follows.

4.2.1 Layer 1 Calibration

The highest degree of calibration and lowest tolerance for spatial trends in residuals is required in Layer 1 because it is subject to stresses applied in the transient simulations and contains most of the features that were critically evaluated in transient simulations to meet model objectives. A plot of steady state residuals for Layer 1 is included in Figure 4-4. Circles used to represent residuals in the figure are sized according to the magnitude of the calculated error and shaded according to the sign of the associated error. A blue circle indicates a positive residual (the computed water level is low compared to the observed water level); while a green circle indicates a negative residual (the computed water level is high compared to the observed water level). Similar to the model-wide calibration, there are more negative residuals in Layer 1 than positive residuals, suggesting that the model tends to over-predict head. Overall, however, positive residuals appear evenly distributed amongst the more numerous negative points.

Potentiometric contours output from the calibrated steady-state model are presented in comparison with the potentiometric surface created during conceptual model development by interpolating between known water levels (Figure 4-5). The simulated potentiometric contours agree favorably with the previously interpolated surface in the immediate mine area where the conceptual model is based on detailed water level data; and the computed head contours offer a fair representation of conceptual flow paths and gradient in areas of the model where data are sparse or absent. The general agreement between the computed and conceptual potentiometric surface maps provides a qualitative measure of the success of the calibration in Layer 1.

4.2.2 Layer 3 Calibration

The distribution of residuals in Layer 3 is presented in Figure 4-6. This plot indicates that predicted heads are in agreement with observed heads at points in the model that represent a minimal amount of separation between the upper and lower Knobloch coal and/or at points where head in the upper and lower coals is nearly the same. These conditions exist in the physical system and are simulated in the model at calibration targets B10-KL, K-2, and K-4. Heads were over-predicted where the amount of separation between the two coals was decreased in the model to accommodate the mine plan. This is evident at the B7-KL target; and resulted in over-prediction greater than two times the residual calibration target at B12-KL.

A comparison of the potentiometric surface generated by the model to the conceptual potentiometric surface for Layer 3 is presented in Figure 4-7. As noted, there are minimal water level observations available with which to construct the conceptual potentiometric surface map, providing a very limited basis for comparison of the two surfaces. The water table contours in the conceptual model necessarily reflect very generalized potentiometric trends due to the paucity of data. In contrast the simulated potentiometric surface of layer 3 is a more detailed assessment of potential flow directions based on the hydrologic relationships defined in the model. The hydraulic gradients and flow directions indicated on the steady state potentiometric surface

generated by the model for Layer 3 are nearly identical to the potentiometric surface generated for Layer 1.

4.2.3 Layer 6 Calibration

Layer 6 Residuals are plotted in Figure 4-8. A comparison of the potentiometric surface generated by the calibrated model to the hand drawn representation of the potentiometric surface for Layer 6 is presented in Figure 4-9. The simulated potentiometric surface is similar to the interpolated potentiometric in the vicinity of Tract 2; however there are discrepancies between the simulated and interpolated surfaces. These discrepancies may be a result of the lack of data or the quality of data used for the interpolated potentiometric map. Water level data for wells completed in Layer 6 are fairly sparse and concentrated in the center of the model. The lack of observation data within the Flowers-Goodale Horizon was a known limitation prior to model development. Although there are large discrepancies between the simulated and interpolated potentiometric surfaces, the majority of the simulated heads are within 10 feet of observed heads and all are well within the 30 foot residual calibration target; therefore the model is calibrated well to known data. The close correlation between observed and simulated heads suggests the vertical gradient between Layer 6 and Layer 1, which is the largest factor for estimating drawdown in Layer 6, is satisfactorily simulated in the vicinity of Tract 2.

4.2.4 Layer 8 Calibration

A plot of residuals in Layer 8 is presented in Figure 4-10. A comparison of the potentiometric surface generated by the calibrated model to the hand drawn representation of the potentiometric surface for Layer 8 is presented in Figure 4-11. Layer 8 was perhaps the easiest to calibrate because it has the lowest range of observed heads, a fairly uniform layer structure, and the fewest calibration targets of all model layers. The minimal number of calibration targets precludes any formal examination of spatial trends.

4.3 CALIBRATION TO RIVER GAINS/LOSSES

The interaction between groundwater and surface water flows was evaluated in the steady state model and used as a secondary calibration objective. Specifically, model budgets for the Otter Creek and Tongue River packages were compared to measured stream flow observations in both surface water features. Discharge in the streams is not calculated by the model directly; but groundwater flow in and out of the river arcs is simulated based on the relationship of head in the model to head in the river. The amount of water that is allowed to flow between the river and adjacent cells is controlled by the constant of proportionality (river conductance). As noted, stream flows used in this secondary calibration were assumed to be representative of baseflow conditions (i.e. groundwater controls gaining or losing conditions). Flow observations used to calibrate the model are much greater than mean daily flows reported for late October for the period of record at Otter Creek (USGS 06307740); thus, calibration to these flows represents a conservative estimate of stream flow interaction.

4.3.1 Otter Creek

The steady state budgets for three reaches identified in the Otter Creek river package are presented in Table 4-3. Reach 1 from Fifteenmile Creek to Tenmile Creek is not gaged; but the steady state budget is presented for later comparison to transient results. A flow budget of -0.27 cfs is predicted from the river package to the model in this reach. In this discussion, a negative budget indicates a losing reach. Note that this is opposite of the MODFLOW convention to report negative budgets as gains to the stream.

Observations made during the baseline study for reach 2, from Tenmile Creek to SW-16, suggest that this a losing reach at baseflow. Stream losses are on the order of 0.1 to 2.4 cfs. A net gain of 0.44 cfs is predicted in the model for this reach (Table 4-3). Steady state output that suggest a gaining flow trend are inconsistent with the physical measurements that indicate that the reach is a minimally gaining reach. However, the magnitude of change in both cases is small. Note that for most of the paired measurements taken at the upstream and downstream gaging stations that define reach 2,

the stream flows are separated by less than one cfs. Measurement error for stream discharge observations can be as much as 20%. All but one pair of stream flow readings (refer to Table 2-5) are within the margin of error, suggesting that this reach is nearly neutral with respect to gains or losses in flow.

The steady state flow budget in the reach of Otter Creek from SW-16 to USGS gaging station 06307740 (Reach 3) is in close agreement with measured stream flow observations. A comparison of the steady state flow budget to flow observations for reach 3 is presented in Table 4-3.

TABLE 4-3. STEADY-STATE CALIBRATION TO OTTER CREEK FLOW OBSERVATIONS

River Reach	Gain/Loss (cfs)			Steady State Model Output			
	min	max	avg	in, cfd	out, cfd	in - out, cfd	in-out, cfs
1.) Otter Creek from Fifteenmile Creek to Tennile Creek	--	--	--	0.80	1.07	-0.27	-0.27
2.) Otter Creek from Tennile Creek to SW-16	-2.41	-0.10	-0.86	1.69	1.25	0.44	0.44
3.) Otter Creek from SW-16 to USGS 06307740	2.30	2.88	2.61	5.23	2.50	2.73	2.73

4.3.2 Tongue River

Inflow to the Tongue River simulated in the steady state model was compared to the rate of gain observed between the USGS Birney Day School and Brandenburg Bridge sites (Table 4-4). The flow budget for the modeled Tongue River package indicated that 1,117,231 cubic feet per day (cfd) flowed from the model to the river and that 926,578 cfd flowed in the opposite direction from the river to the model. Thus, the total river gains were calculated as the difference between flow in and flow out (190,653 cfd). The resulting flow budget was converted to units of cfs and divided by the boundary arc length to obtain a dimensionally comparative result. Tongue River gains calculated from

the final calibrated steady state model were 0.1 cfs/mile, which are within the range estimated from long-term USGS measurements.

TABLE 4-4. STEADY STATE CALIBRATION TO TONGUE RIVER FLOW OBSERVATIONS

River Reach	Rate of gain (cfs/mile) /2			River Reach	Model Output		Length of Reach (miles)	Rate of gain (cfs/mile)
	min	max	avg		cfd	cfs		min
USGS Birney Day School to Brandenburg Bridge	0.085	0.35	0.22	Birney to Ashland, MT	190653	2.2	21.6	0.102

4.4 CALIBRATION TO ESTIMATED GROUNDWATER FLUX

In addition to calibrating the model to heads and boundary conditions, the model was calibrated to groundwater flux. Flux calculations and potentiometric surface interpolation are based on approximations of flow area geometry, are subject to hydrologic interpretation, and have a higher degree of uncertainty stemming from lower precision of measurement. Measurements of head can realistically be made to the nearest 0.01 foot; while, flux calculations may only be accurate to within 20 percent of actual values. However, it is important to evaluate steady state flux to identify potential discrepancies between conceptual and numerical flow budgets. Model calibration to flux calculated by Darcy’s Law was used as a secondary objective of model calibration.

4.4.1 Alluvium

Steady state flow budgets were exported from the model for five alluvial cross sections and compared to representative baseline Darcy flux estimates, as shown in Table 4-5. The flow budgets are representative of simulated flux through Otter Creek alluvium at the south and north ends of the model and in the Tenmile Creek, Threemile Creek, and Home Creek ephemeral tributaries near their confluence with Otter Creek. In general, model flow budgets are in agreement with estimates made using Darcy’s Law. Inflow to the model at the southern Otter Creek GHB was 204 gpm. Outflow at the north GHB was

558 gpm. The outflow GHB is representative of gaining conditions in alluvial flux as the modeled alluvium widens at the confluence between the Tongue River and Otter Creek. Flux in the Home Creek Tributary is nearly twice that estimated by Darcy's Law. The flow estimate through Home Creek Alluvium was based on a single aquifer test conducted in this drainage. Model parameters were varied within reasonable ranges to achieve primary calibration to observed heads.

TABLE 4-5. STEADY STATE CALIBRATION TO FLUX IN ALLUVIUM

Hydrogeologic Unit	Darcy's Law Estimated Groundwater Flux	MODFLOW Simulated Flux
	gpm	gpm
Otter Creek Alluvium Inflow	1 - 1209	204
Otter Creek Alluvium Outflow *	1 - 1209	558
Home Creek Alluvium	130	240
Threemile Creek Alluvium	122	126
Tenmile Creek Alluvium	97	109

*Boundary outflow includes both Tongue River and Otter Creek Alluvium

4.4.2 Knobloch Coal (Layers 1 through 3)

A comparison of model flow budgets to flux estimates made in the conceptual model are presented in Table 4 – 6, below. Inflow through the GHB on the east side of the model is within the expected range of Darcy flow estimates perpendicular to a cross section of equivalent length to the boundary. The relatively low estimate of flux at the boundary is applicable to the boundary which is assumed to be near a groundwater divide in the physical system and was parameterized so as not to interfere with drawdown in the model. The steady state flow budget for the mine area is also consistent with previous estimates of flux made in the conceptual model. Increased flux in the mine area of the model reflects input from upgradient recharge and increased K assigned to the model near crop and burn lines on the margins of alluvial and clinker parameter zones.

TABLE 4-6. CALIBRATION TO FLUX IN KNOBLOCH COAL

Hydrogeologic Unit	Estimated Groundwater Flux (gpm)			MODFLOW Simulated Flux
	min	max	Avg.	gpm
Knobloch Coal -- East Model Boundary	3	2599	359	216
Knobloch Coal - Mine Area	5	585	157	268

4.4.3 Underburden (Layers 6 and 8)

Steady state groundwater flux through GHB in Layers 6 and 8 are compared to Darcy's flux estimates made in the conceptual model in Table 4-7, below. Flow estimates exported from the model are cumulative of GHB on the south and east sides of each of Layers 6 and 8; thus, total boundary length is 233,400 feet. Flux estimates at model boundaries are near the low end of the expected range.

MODFLOW is a saturated media model; thus, a potentially overstated hydraulic connection is inherent between all layers of a given model. Flow through the upper face of cells into Layer 6 in the calibrated model was approximately 10,469 cubic feet per day (54.4 gpm). This is more than four times that introduced by the GHB. When coupled with flow from the GHB, the Layer budget is 67.4 gpm and provides a reasonable approximation to flux estimated in the conceptual model by Darcy's Law. Table 4-7 presents a very broad range of flux conditions that could result in the physical system in localized areas if certain hydraulic properties coincide (i.e. minimal saturated thickness coincident with low hydraulic conductivity); however, the extreme ends of the ranges are not reasonable targets for model calibration. The Otter Creek groundwater model was primarily calibrated to observed head. Because the source of water that resulted in calibrated head in Layer 6 in the steady state simulation was from overlying strata (model layers), Layer 6 will be more responsive to influence from stresses in overlaying layers. Flow through the upper face of Layer 8 was actually negative (-580 cubic feet per day),

suggesting that seepage from upper layers is a less influential source of water in this layer. Hydraulic conductivity of aquitard Layers 5 and 7 controls the amount of water into or out of aquifer Layers 6 and 8. Model sensitivity to hydraulic conductivity of the aquitard layers is evaluated in Section 6 of this report.

TABLE 4-7. CALIBRATION TO BOUNDARY FLUX LAYERS 6 AND 8

Hydrogeologic Unit	Estimated Groundwater Flux (gpm)			MODFLOW Simulated Flux
	min	max	Avg.	gpm
Flowers-Goodale Horizon (Layer 6)	0.7	1588.0	106.0	13
Deep Sandstone Horizon (Layer 8)	6.5	137.9	62.9	19

5.0 GROUNDWATER FLOW MODEL PREDICTIVE SIMULATIONS

Transient predictive simulations were performed for the Tract 2 mine dewatering sequence using the parameters and procedures outlined in Section 3 above. Transient simulations used to predict drawdown outside of the mine area were performed under the conservative assumption that re-circulated groundwater pumped from the mine did not influence drawdown and/or flow budgets from other features. Results of the transient simulations are included herein and include the following:

- Estimates of volumetric dewatering rates;
- Predicted spatiotemporal drawdown response to dewatering that includes not only the mine area but also the off-site radius of influence;
- Simulated effects of mine dewatering on groundwater/surface water interaction in Otter Creek; and
- Projected long term water level recovery rates.

5.1 DEWATERING RATES

Dewatering simulations were conducted as described in Section 3.9. Model output suggests that dewatering rates will be highest during the initial two years of mining that take place nearest Otter Creek Alluvium and the clinker groundwater reservoir but that elevated dewatering rates are also predicted at locations within the mine area where the coal base elevation is the lowest.

Peak drain budgets reached values in excess of 3,000 gpm in transient life of mine simulations and the geometric mean budget for years one through four was 833 gpm. The geometric mean of drain budgets over the life of mine was 647 gpm. As noted in Section 3.8.1, mine dewatering simulated with the use of drains results in artificially high dewatering rates each time a drain is activated in the model. This is due to the model instantaneously lowering the head to the assigned drain elevation (base of Knobloch coal) over a large area. The proposed mine plan is to remove water as the overburden and coal are excavated. Dewatering in accordance with the mine plan will result in much lower

initial dewatering rates, as the full thickness of the aquifer is not encountered until the cut reaches the base of the coal. The process of dewatering and removing material will take 30 or more days for each cut. Over this time the water table will be gradually lowered resulting in a more consistent dewatering rate than the model simulates. The dewatering rate at the end of each stress period is the most applicable to projections of anticipated mine dewatering rates. A hydrograph of final anticipated dewatering rates was constructed from model drain budgets at the end of each stress period and is included in Figure 5-1.

The predicted dewatering rates ranged from greater than 1500 gpm to less than 100 gpm throughout the mine life (19 years). A geometric mean of approximately 391 gpm was calculated for the life of mine (Figure 5-1). The highest dewatering rates were simulated during the first four years of mining (Range: 181 - 1556 gpm; Geometric Mean: 601gpm) and are attributable to the proximity of the mine to the clinker and Otter Creek alluvial system. Note that similar transient pit inflows were predicted by the analytical line-sink model (Figure 2-9). Flow estimates made by the line-sink analysis ranged from 608 gpm after one day to 130 gpm after one year. The mine cut considered in the line sink analysis was comparable in size (length) to many of the drains simulated in the numerical model. However, the flow rates are not necessarily directly comparable because of the assumption of aquifer heterogeneity that is inherent in the line sink equation. As demonstrated in the numerical model, pit inflows are expected to be greatest where mine cuts are adjacent to bodies with high hydraulic conductivity and greater storage capacity (i.e. clinker and alluvium). Pit inflows estimated by the line sink analysis may be most representative of conditions at the far east side of the mine area where the influence of other hydraulic units is less pronounced.

It is appropriate to estimate final dewatering rates using drain budgets from the end of each stress period; however, it is important to note that model output and predictions related to stresses from drains are still subject to the highest rates predicted by the numerical model. Artificially high drain budgets will impact model budgets related to other hydrogeologic features (e.g. Otter Creek) included in the model.

5.2 DRAWDOWN PREDICTIONS AND RECOVERY RATE ESTIMATES

The transient model was used to predict drawdown in the mine area and in adjacent aquifers attributable to mine dewatering in Tract 2. Drawdown simulated by the model was greatest in Layer 1, as it was subject to the highest degree of transient stress. Potentiometric surfaces generated by the model for Layer 1 during the mine dewatering simulation are mapped in Figure 5-2. Simulated drawdown contours are mapped in Figure 5-3. As specified previously, head and drawdown were exported from the model at the end of each of the two year cascading simulations and at the conclusion of the final year of simulation (year 19).

The simulated maximum extent of the five foot drawdown contour is presented in Figure 5-4. East of the mine, drawdown of five feet or greater reached a radius of approximately 9.2 miles. Northeast and southeast of the mine area, drawdown was exacerbated by boundary condition effects. Boundary condition effects are apparent by the perpendicular orientation of the drawdown contour to the model boundary at their points of intersection. While not desirable, this boundary condition effect results in a conservative estimate of simulated drawdown. Model sensitivity to GHB conductance is tested in Section 6.

Simulated drawdown increased to the north, south, and east of the mine area as mine dewatering progressed in the model. However, drawdown was attenuated at the mouths of Tenmile and Threemile Creek drainages where alluvium is modeled in connection with the coal. Similarly, simulated drawdown was greatly reduced west of the mine area in alluvium of Otter Creek. Less than five feet of drawdown were predicted throughout Otter Creek alluvium and clinker on the east side of Otter Creek. Drawdown was predicted west of Otter Creek but none in excess of the five foot drawdown contour. Maximum drawdown west of the creek was approximately two feet in each of Layers 1, 2, and 3. Similarly, maximum drawdown predicted in the first underburden aquifer in the model (Flowers-Goodale, Layer 6) was slightly greater than two feet. Flow patterns predicted in Layer 6 did not change appreciably during the dewatering simulation. Head and drawdown predicted by the model in Layer 6 at the end of the mine dewatering

simulation are included in Figure 5-5. The maximum extent of drawdown in all layers occurred at the end of mining simulation in year 19.

Hydrographs of simulated water level elevations at select wells outside of the mine area are presented in Figure 5-6. The hydrographs indicate that the magnitude of predicted mine influence on water levels is a function of proximity to the mine area, lithology present at the well, and the presence or absence of a hydrologic boundary (i.e. Otter Creek, alluvium or clinker, or underburden confining layer).

Knobloch Coal – Drawdown predicted by the transient model was greatest in Layer 1 at locations parameterized by Knobloch coal properties that were not separated from the mine area by a hydrologic boundary. Hydrographs for wells 7421 (northeast of the mine area) and B12-UK1 (southeast of the mine area) illustrate this point (Figure 5-6). The predicted water level declined in well 7421 by approximately 15 feet by the end of the mine dewatering simulation; and the predicted water level declined by approximately 30 feet at well B12-UK1 by the end of the mine dewatering simulation. Drawdown at well B4-K, which is closer to the mine area than well 7421, was moderate compared to that predicted at well 7421, due to the presence of Threemile Creek alluvium north of the mine area.

The predicted hydrograph at well K-5, located in the coal buffer zone east of the mine, exhibited an oscillatory response to the activation/deactivation of drains used to simulate mine dewatering. Rapid responses to stress are expected at this well given its proximity to the mine area. Note, however, that the magnitude of water level decline at this simulated observation point was dampened by the connection to the clinker body immediately to the west. Observation points in coal of Layer 1 opposite Otter creek (e.g. B8-KU and B9-K) exhibited much less drawdown. As noted, predicted drawdown opposite of Otter Creek was greatest at locations immediately adjacent to the mine; but a maximum water level decline of approximately two feet was predicted. Maximum water level declines predicted at B8-KU and B9-K were 0.65 feet and 1.65 feet, respectively.

A hydrograph for B12-KL is included to provide comparison between model predictions for Layer 1 and Layer 3. Note that the hydrograph for B12-KL, representative of Lower Knobloch coal Layer 3, is nearly identical to that at B12-UK1 in Layer 1. Projections made by the model regarding influences on the lower coal unit are conservative but appropriate given the direct hydrologic connection between the separated coal seams.

Clinker – The simulated hydrograph for well C-3 indicates that gradual but discernible changes in clinker water levels are predicted by the model. The maximum decline in water level predicted at C-3 was 2.2 feet. This is likely a conservative projection based on the relatively low K assigned to clinker in the model.

Alluvium – Simulated hydrographs for representative alluvial observation wells (A3, A6, A7, and A8) generated by the transient model, are included in Figure 5-6. Water levels declined by less than two feet in the alluvial observation wells during simulated mine dewatering. The maximum water level decline was observed at well A6, less than one mile west of the mine area. Approximately 1.6 feet of drawdown were predicted at A6 during the simulation.

Underburden – The B11 battery is located inside the mine area and will be removed during mining. However, minimal drawdown that was predicted by the model in Layer 6 (Flowers-Goodale/first sandstone) was coincident with this well battery. The simulated hydrograph at observation well B11-U suggests a water level decline of 1.5 feet during mining. However, as post-mine water levels in the mine area increased, water levels also rose in the first underburden.

Water level recovery predicted by the model at the end of the mine dewatering simulation is illustrated in Figure 5-7; and potentiometric head output from the post-mine simulation is included in Figure 5-8 for the first 50 years. Note that the post-mine simulation was conducted for 500 years; but water levels recovered to levels equal to or greater than steady state potential by approximately 50 years. Water level recovery to heads greater than starting heads was observed in the model upgradient of the mine area and is

attributable to the decreased hydraulic conductivity assigned to the spoils. Conversely, delayed recovery at locations downgradient of the mine area is the result of increased storage in the spoils. Recall that mine spoils specific yield was increased to 0.12 from the coal specific yield value of 0.05. Spoils hydraulic properties are considered in the sensitivity analysis in Section 6.

Zone budgets exported from the transient post-mine model indicate that groundwater flow proceeded from (through) the coal buffer into the mine area for a period of 25 to 30 years after the end of mining. Flow from the spoils to the coal buffer gained in magnitude for 40 years before reaching quasi-steady state conditions in year 70 of the post-mine simulation. The final flow budget from spoils to coal buffer at the end of the 500 year simulation was 110 gpm. The pre-mine steady state budget from Knobloch coal to the coal buffer zone was 204 gpm. Again, reduced flow through the buffer after the mine dewatering simulation is a function of low K parameters assigned to the spoils. Flow paths from the spoils, simulated by MODPATH particle analysis in the post-mine model, are presented in Figure 5-9. These flow paths indicate that groundwater travels to the large clinker body west of the mine before proceeding northward through alluvium of Threemile creek and a second clinker deposit to the north.

5.3 STREAM FLOW INTERACTION WITH GROUNDWATER

A hydrograph of Otter Creek gains and/or losses, calculated within the transient flow model, is presented in Figure 5-10. As outlined, budgets for three separate reaches are included: Reach 1) from Fifteenmile Creek to Tenmile Creek; Reach 2) from Tenmile Creek to SW-16 (A6); and Reach 3) from A6 to the USGS gaging station at Ashland. Baseflow in the calibrated steady state model for reaches 1, 2, and 3 was -0.27 cfs, 0.44 cfs, and 2.73 cfs, respectively. Baseflow conditions are presented in the hydrograph as a solid horizontal line for each reach. Transient flow conditions are presented in the hydrograph for each reach using markers that are color-coordinated with the steady state values.

Reach 1, upstream of the mine area, did not exhibit a perceptible change in groundwater flow to surface water in the model under transient conditions. This is evident by the alignment of transient markers with the steady state baseline. All departures from the steady state baseline were less than 0.1 cfs. These model results suggest that mining impacts on Otter Creek upstream of the area of development will be negligible.

Reach 2, adjacent to the mine area, exhibited the greatest changes in groundwater contribution to surface water during the period of mine dewatering in the transient simulation. The steady state prediction of stream gains from groundwater in this reach was 0.44 cfs. By the end of year two in the simulation, the model predicted that Reach 2 was a losing reach on the order of -0.79 cfs, resulting in a cumulative change of 1.2 cfs. Peak changes in predicted river leakage were limited to the first two years of mining; then, the model predicted that river losses reached quasi-equilibrium (at approximately -0.2 cfs) for the remainder of the dewatering stress periods (years 3 through 19). At -0.2 cfs, the cumulative change in river leakage from the steady state budget is 0.64 cfs. At the end of dewatering stress periods, river leakage trended back to the steady state value of 0.44 cfs. The predicted lag in recovery time is attributable to the increase in storage of the spoils.

Gaining conditions were maintained throughout the transient simulation in downstream Reach 3; but estimates reduction in flow to the river reached a maximum of 0.53 cfs at the end of year 2 of the mine dewatering simulation. Steady state flow to the river was 2.73 cfs; while flow to the river at the end of year two was 2.2 cfs.

It should be noted that the model only approximates river budgets to or from groundwater. The model does not explicitly calculate flow in the creek. In this case, modeled predictions of Otter Creek gains and/or losses are very conservative for two key reasons: 1.) the steady state model was calibrated to stream flow conditions, assumed to be baseflow conditions, that are greater than the average daily flow value for the modeled time period; and 2.) drain budgets calculated in the model are much greater than those that can reasonably be achieved by pumping in the physical system. By calibrating to

higher than normal baseflow conditions, connectivity (i.e. river conductance) between the river package and simulated groundwater aquifer may be overestimated; and peak drain budgets that are only attainable in the numerical model will result in influences that are also only attainable in a model.

Even under the conservative assumptions discussed above, the predicted influences of mine dewatering on Otter Creek surface flows in reaches adjacent to and downgradient of the mine do not translate to significant impacts. If the flow regime used to develop the model is considered, flow in Otter Creek in Reach 2 ranges from 2.1 to 5.5 cfs. The maximum decrease in flow in Reach 2 at the end of year 2 predicted by the model was 1.2 cfs; thus, 0.9 to 4.3 cfs would remain in Otter Creek. These values are consistent with or greater than the mean daily flows in late October for the period of record at USGS 06307740. Further comparison can be made to the entire range of flows observed during the period of record at the gaging station. As outlined in the Baseline Water Resources Report 304E, mean monthly discharge is greatest in March and is equal to 13 cfs. Stream depletion predicted by the model would be imperceptible under these flow conditions. Additional analyses of flow data suggest that Otter Creek is prone to drying completely in approximately 30% of water years (also noted in 304E); thus, complete but temporary stream depletion is within the normal range of hydrologic observation at Otter Creek. However, even under the conservative assumptions included in the model, the model does not predict levels of river leakage that would equate to complete depletion.

River leakage into and out of the Tongue River was unaffected by transient stresses applied in the mine dewatering simulation.

6.0 SENSITIVITY ANALYSIS

Sensitivity analysis was conducted on source/sink parameters and areal properties that were believed to have the most influence on the attainment of model objectives identified in Section 1 of this report. Parameters varied in the sensitivity analysis included hydraulic properties of the Knobloch coal, hydraulic properties of underburden aquitards, GHB parameters, and river conductance. Justification, methodology, and results of the sensitivity analysis are as follows.

6.1 KNOBLOCH COAL HYDRAULIC CONDUCTIVITY

Justification – Areal properties of cells representing the Knobloch coal in and around the mine area have the potential to affect model predictions, as stresses were applied to these units in transient dewatering simulations. Specifically, these parameters will directly influence drain budgets, the amount of drawdown, and rate of recovery predicted in the coal aquifer adjacent to the mine. K of the coal is fairly well characterized; but is found to vary from 0.1 to 10 ft/day.

Evaluation

- Values of Knobloch coal K used in Layer 1 were varied from calibrated values by \pm two times the values applied in steady-state simulations. K of coal in Layer 1 ranged from 0.5 to 10 ft/day in the calibrated model. Values were adjusted to range from 0.25 to 5 ft/day in the reduced K simulation of the sensitivity analysis; conversely, values were adjusted to range from 1 to 20 ft/day in the simulation with increased K values. Note that K of 20 ft/day were only assigned in isolated parameter zones on margins of alluvium that were previously assigned a value of 10 ft/day. The highest K in the mine area during this simulation was 9.5 ft/day. Model sensitivity was evaluated by comparing resultant heads to the calibrated steady state heads on the basis of mean absolute residual; and the extent of drawdown during mine dewatering assuming reduced and increased K values was compared to the previous estimate of drawdown at the end of years 2, 6, 10, 14, and 19 (end of mining) in the transient model.

Results –

- Increased K in Layer 1 resulted in an increase in mean absolute residual from 7.22, in the calibrated steady state model, to 7.94. Increased error was the result of a general decline in heads in Layer 1. Conversely, decreased K in Layer 1 produced a mean absolute error of 9.55 that was attributable to a model-wide increase in computed head. Computed and residual heads output from the evaluation of increased and decreased coal K are included with results of other model parameters evaluated in this sensitivity analysis in Table 6-1, attached. Based on steady state results, the model appears relatively insensitive to K values within the range observed during baseline study, especially those on the upper end of the estimated range.
- Head and drawdown predicted at the end of years 2, 6, 10, 14, and 19 of the dewatering simulation parameterized by increased hydraulic conductivity are presented on contour maps in Figure 6-1. Head and Drawdown contour maps generated for the reduced K evaluation are included in Figure 6-2. Drawdown was more extensive in the transient simulation when higher K was considered and less extensive in the transient simulation when the lower K was considered; but neither case changed the conservative prediction of drawdown appreciably. The final five-foot drawdown contours predicted by the high K, low K, and calibrated models are plotted concentrically in Figure 6-3. Distance to the five-foot contour east of the mine area ranged from 8.7 to 9.6 miles. Consistent with the steady-state evaluation, transient results indicate that the model is not overly sensitive to Knobloch coal K within the observed range.

6.2 KNOBLOCH COAL SPECIFIC STORAGE

Justification – Specific storage estimates from baseline aquifer tests ranged from 0.0009 to 2.3×10^{-6} . The average specific storage value for coal units reviewed by Rehm et al. (1980) was $6 \times 10^{-5} \text{ ft}^{-1}$. To provide a conservative estimate of drawdown, a low storage coefficient of 2.3×10^{-6} was assigned to transient simulations discussed above. An evaluation of the assertion that this is a conservative estimate is conducted in this sensitivity analysis by assigning higher value of the specific storage parameter.

Evaluation - Specific storage has no effect on steady state output; so model sensitivity to specific storage was only evaluated via a transient simulation. In the sensitivity simulation, specific storage of representative coal units was increased by a factor of ten to 2.3×10^{-5} . The extent of the five foot drawdown contour was compared to initial estimates made using the lower storage coefficient.

Results – Drawdown predicted at the end of each stress period in the dewatering sequence was attenuated compared to that predicted by the calibrated base model. Head and drawdown output for years 2, 6, 10, 14, and 19 are presented in Figure 6-4. Note that the maximum extent of the predicted five foot drawdown contour east of the mine area was reduced from approximately 9.2 miles in the conservative base model to 6.7 miles in the simulation with an increased storage coefficient. This analysis confirms that a conservative estimate of drawdown was predicted by the calibrated model; and given uncertainty of the actual distribution of the storage coefficient, drawdown outside of the mine area may be highly variable.

6.3 GHB CONDUCTANCE

Justification – Drawdown predictions may be limited or exacerbated near model boundaries where boundary conditions are not appropriately parameterized. As seen in drawdown predictions presented previously for the Otter Creek model, drawdown north and south of the mine area, cross-gradient of the baseline direction of flow, is over-predicted because conductance of the north and south GHB was parameterized to allow a minimal amount of water across the boundaries under simulated baseline conditions. The influence of the boundary conditions is apparent because drawdown contours are perpendicular to and intersect the model boundary. The intent of the current assignment of GHB conductance was to provide a conservative estimate of drawdown. A conservative estimate was made; and north and south boundary influences are considered insignificant because they occur at a drawdown interval (~ 5 ft) that is equal to or less than the mean absolute residual of the calibrated model (7.22 ft). The east GHB appears to be appropriately parameterized, as it does not restrict drawdown in the transient

simulations. Note that the five foot drawdown contour advances in each successive stress period during transient simulations.

Evaluation – GHB conductance was evaluated by varying values of this parameter assigned to the north, east, and south boundaries of Layer 1. Minimum and maximum values that define the range of estimated GHB conductance for these boundaries, presented previously in Table 3-6, were tested. A minimum value of $0.00035 \text{ ft}^2/\text{day}/\text{ft}$ was applied to all three boundaries in steady-state and transient model simulations. Similarly, maximum values of $0.035 \text{ ft}^2/\text{day}/\text{ft}$ for the north and south boundaries and $0.1 \text{ ft}^2/\text{day}/\text{ft}$ for the east boundary were assigned to steady-state and transient runs. Steady state output were compared on the basis of mean absolute residual head. Transient runs were compared by reviewing the extent of drawdown and the relationship of drawdown contours to model boundaries.

Results -- Mean absolute residuals for either of the adjusted boundary conditions were greater than that of the calibrated model. Under conditions of increased GHB conductance, the eastern extent of the five foot drawdown contour was only slightly decreased as compared to that predicted using the calibrated GHB conductance. This suggests that boundary condition effects that would limit drawdown in the east, if present, are minimal. However, the reason for the decreased extent to the five foot contour under the higher GHB conductance may be from the decreased residual drawdown effect from the north and south boundaries. Increased GHB conductance at these boundaries allowed flux into the model and resulted in drawdown contours that were not influenced by lateral flow limitations. Decreased GHB in the transient model produced boundary effects that were more pronounced than previously observed in the base transient simulation. Head and drawdown contours created to evaluate model sensitivity to increased and decreased GHB conductance are shown in Figures 6-5 and 6-6, respectively.

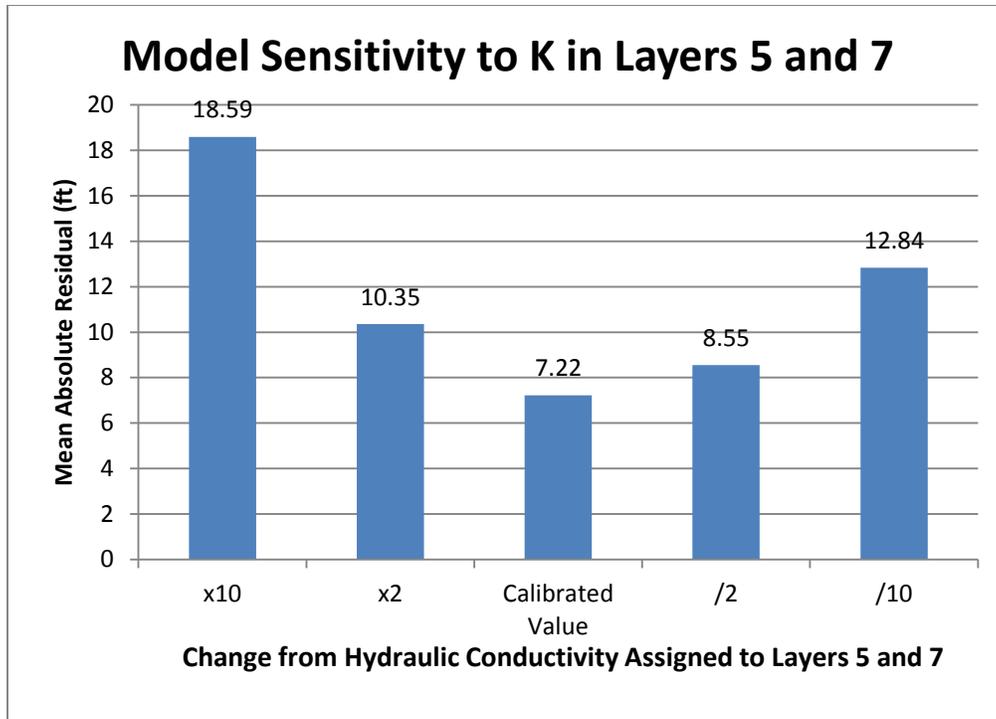
6.4 HYDRAULIC CONDUCTIVITY OF UNDERBURDEN AQUITARDS

Justification – Hydrologic properties of siltstone and shale underburden aquitards in the model were not estimated explicitly during the baseline study; so values used to represent confining layers in the model were from published sources. Specifically, values applied were representative of a range of hydraulic conductivities published for siltstone sedimentary bedrock. Layers 5 and 7 were assigned the lowest values of siltstone K used in the model ($K = 2.83 \times 10^{-6}$ ft/day); thus, the K of these layers is the limiting factor in the prediction of drawdown in underburden aquifers. The values used in transient simulations are conservative based on the fact that siltstone is more permeable than shale (no shale K was used); but in most cases, shale or claystone is present in some fraction of the underburden bedrock. The continuity and heterogeneity of these layers is uncertain given the nature of the Fort Union Formation that they represent.

Evaluation – Values of underburden K used in Layers 5 and 7 were increased and decreased from calibrated values by factors of two and ten and applied in steady-state simulations. Resultant heads were compared to the calibrated steady state heads on the basis of mean absolute error.

Results

Based on the comparison of steady state mean absolute residuals, the model calibration appeared to be sensitive to K of underburden confining Layers 5 and 7. A plot of the mean absolute residuals for varied input, as compared to the mean absolute residual for calibrated K, is as follows.



Heads in the steady state model populated with increased and decreased K in Layers 5 and 7 did not meet calibration criteria established in Section 4; and a transient simulation was not conducted with these parameters. As previously mentioned, the use of an effective porous media model has inherent limitations at simulating hydrostratigraphy that have limited connectivity. As such, the connection between upper and lower aquifers appears to be adequately represented in the calibrated model.

6.5 SPOILS HYDRAULIC CONDUCTIVITY

Justification –Hydraulic conductivity of the spoils have the potential to affect dewatering rates in the transient mining simulation and water level recovery rates and flow patterns in post-mine simulations. Hydraulic conductivity assigned to spoils as they replaced the coal aquifer in the transient simulation was 0.25 ft/day. This estimate was based on the geometric mean value reviewed by Rehm (1980). However, a range of spoils K from 0.04 ft/day to 5.6 ft/day was estimated for spoils in the Colstrip, MT area (Van Voast et al., 1977). Spoils in the Colstrip, MT area are of consistent parent material and are likely to be similar in hydrogeologic properties to those at Otter Creek. Note the K of Colstrip,

MT spoils are actually consistent with the range of K calculated in the baseline study for undisturbed coal aquifers in the Otter Creek area.

Evaluation – A transient simulation was conducted, in which hydraulic conductivity was not changed in the model as mining advanced. Consistent with previous transient simulations, specific yield of the spoils was changed from 0.05 (representative of coal) to 0.12 (representative of spoils) as spoils replaced the coal in the model. Model output were evaluated for changes in head and drawdown in both dewatering and post-mine recovery simulations.

Results – Head and drawdown contours output from the model during the mine dewatering simulation are presented in Figure 6-7. Head and drawdown predictions made by the post-mine model are shown in Figure 6-8. Water level recovery times predicted by the model were reduced from approximately 50 years to 15 to 20 years when K of the spoils was assumed equal to K of the Knobloch coal.

6.6 RIVER CONDUCTANCE

Justification – River conductance may affect head in cells adjacent to river arcs included in the model to represent the Tongue River and Otter Creek. More importantly, river conductance is the primary factor in groundwater/surface water interactions predicted by the model. River conductance was varied during model calibration to provide the highest level of agreement with observed head and to approximate gaining and losing reaches along Otter Creek. Based on the occurrence of fine-grained river bed materials in both the Tongue River and Otter Creek, river conductance is expected to be low. However, river conductance may be highly variable given the presence of clinker or gravel of clinker parent materials that are also found underlying the stream beds.

Evaluation – Model sensitivity to river conductance was evaluated in steady state and transient model simulations. Conductance of arcs used in the model to represent Otter Creek and Tongue River were increased/decreased by four times the values used in the calibrated model. Changes in steady state mean absolute error and river leakage budgets

were compared to values calculated for the calibrated steady state model; then, effects on the transient simulations were evaluated by comparing river leakage budgets resultant from increased/decreased conductance with those used in the previously discussed mine dewatering simulations. In particular, river leakage budgets for Reach 2 of Otter Creek were compared to those output in the first four years of the mine dewatering simulations discussed in Section 5.

Results -- Steady state River Package flow budgets for each of the three reaches of Otter Creek and the Tongue River are presented for the varied range of river conductance parameters in Table 6-2, attached. Based on the flow budgets, sensitivity to river conductance varies greatly by reach. Our modeled representation of the Tongue River and Reach 3 of Otter Creek were insensitive to changes in river conductance; while, reaches 1 and 2 of Otter Creek were influenced greatly by changes to this parameter.

Gains predicted at steady state for the Tongue River ranged from 2.16 cfs to 2.32 cfs, when river conductance was increased/decreased. A gain of 2.2 cfs was predicted for the Tongue River in the calibrated steady state model, indicating that our modeled representation of the Tongue River is not sensitive to changes in the conductance parameter. Similarly, gains calculated in Reach 3 of Otter Creek did not exhibit sensitivity to varied river conductance parameterization. Predicted gains in Reach 3 ranged from 2.69 cfs (increased conductance) to 2.75 cfs (decreased conductance), compared to a gain of 2.73 cfs predicted by the calibrated model.

Reaches 1 and 2 of Otter Creek exhibited a high degree of sensitivity to changes in the river conductance parameter. Reach 1 was predicted to be a mild losing reach (-0.27 cfs) in the calibrated steady state model. Under conditions of higher river conductance ($c = 10 \text{ ft}^2/\text{day}/\text{ft}$), losses from this reach were predicted to be more than five times greater (-1.37 cfs). Conversely, under decreased conductance ($0.625 \text{ ft}^2/\text{day}/\text{ft}$), Reach 1 was predicted as a gaining reach (0.22 cfs) nearly equal in magnitude but opposite of the losses predicted by the calibrated model. Similar sensitivity to river conductance was observed at Reach 2. This reach was predicted as a gaining reach (0.44 cfs) in the steady state

calibration, despite field observations that indicate it is most likely a losing reach during the time period considered in the model. However, most of the losses observed in the physical system in this reach were minimal. Under an assigned river conductance of 10 ft²/day/ft, Reach 2 was predicted to gain 1.36 cfs. The gain resulting from increased river conductance is greater than four times the value predicted in the steady state calibration. Decreased river conductance had the opposite effect on predicted Reach 2 gains. When the river conductance was reduced, a gain of just 0.03 cfs was predicted at Reach 2. Although Reach 2 is still predicted to be a gaining reach under this parameter assignment, the predicted value is in closest agreement with the mild losing conditions observed in the field.

The mean absolute residual did not change appreciably as river conductance was varied. Mean absolute residual values calculated for the calibrated model, decreased river conductance simulation, and increased river conductance simulation were 7.22, 7.83, and 7.32, respectively. Steady state residuals for each of the three simulations are included in Table 6-1, attached. This comparison suggests that the overall prediction of steady state head is not sensitive to changes in river conductance. However, predictions of head are sensitive to river conductance at calibration targets nearest to river arcs.

Based on steady state results, the upper reaches of Otter Creek, upstream and adjacent to the area of mine development, are apparently the most sensitive to variation in river conductance. As evaluated in transient simulations above, Reach 2 is also the most susceptible to stream flow influences from mine dewatering. Transient model simulations were conducted to further examine the effect of river conductance on predictions of groundwater/surface water interaction in Reach 2 during mine dewatering. A hydrograph of results was constructed and is included in Figure 6-9, attached. The condition of increased river conductance ($c = 10$ ft²/day/ft) resulted in a river leakage response that was consistent in pattern with the base transient prediction but exhibited a higher overall level of depletion in the first four years of the simulation. At the start of the transient simulation of increased river conductance, Reach 2 was gaining at 1.36 cfs. After year two of the four-year simulation, net gains were depleted to 0 cfs, resulting in a

maximum depletion of 1.36 cfs. The overall rate of depletion at the end of year two in the baseline transient simulation was 1.22 cfs.

Mine dewatering effects on river leakage were decreased when the lower river conductance (0.625 ft²/day/ft) was applied to Reach 2. The reach exhibited a similar but more gradual pattern of river leakage compared to the calibrated model parameter. Net depletion in Reach 2, when decreased conductance was assigned, was just 0.68 cfs. Model output suggested that the reach was gaining at 0.03 cfs at the start of the simulation but trended to a losing pattern (-0.65 cfs) in the end of year 2.

This evaluation of model sensitivity to river conductance in regards to predicting observed river gain/loss conditions indicates that a lower conductance parameter may be appropriate for the upper reaches of Otter Creek. However, the chosen value was part of a parameter set that produced a better overall agreement to observed heads; also, river conductance used in initial transient simulations resulted in a more conservative estimate of stream depletion.

7.0 EVALUATION OF MODEL RESULTS

The conclusion of this report includes a summary of results and a discussion of potential limitations of the Otter Creek Mine groundwater flow model.

7.1 SUMMARY OF RESULTS

Results of this modeling effort are as follows.

- A steady-state numerical model was constructed and calibrated using values of hydrogeologic parameters consistent with those measured during baseline site investigation in key strata (i.e. Knobloch Coal, Otter Creek Alluvium, Clinker, and underburden aquifers) found in and around the proposed Otter Creek mine. A level one calibration to potentiometric head was attained at 77 of 81 calibration targets used in the model. Pre-mine potentiometric head and groundwater flux through key hydrogeologic strata were well-represented in the calibrated steady state model.
- Pre-mine surface water gains and losses in the Tongue River and reaches of Otter Creek adjacent to the Tract 2 mine area were simulated in the calibrated steady state model. Specifically, the steady state simulation was calibrated using surface water flow observations made in the months of September through November during the baseline hydrology study. Data gathered in the study and used in the model represented higher than normal stream flow conditions in Otter Creek.
- Groundwater inflow rates/dewatering rates to open mine cuts were evaluated over the period of mine development in transient model simulations using the MODFLOW Drain Package. The Drain Package tends to grossly over-estimate peak pit inflow rates because heads are instantaneously lowered to the assigned drain elevation (base of Knobloch coal), sometimes over a large area. However predictions of dewatering rates were estimated by assuming that drain budgets output in the last time step of each stress period were most representative of those that may be encountered during mine development. The predicted dewatering rates ranged from greater than 1500 gpm to less than 100 gpm throughout the

mine life (19 years). A geometric mean of approximately 391 gpm was calculated for the life of mine (Figure 5-1). The highest dewatering rates were simulated during the first four years of mining (Range: 181 - 1556 gpm; Geometric Mean: 601gpm) and are attributable to the proximity of the mine to the clinker and Otter Creek alluvial system.

- Drawdown in principal aquifers surrounding the Otter Creek mine was assessed in mine dewatering simulations by comparing calibrated heads from the steady state model to transient head output. Specifically, the model was used to predict the extent of the five-foot drawdown contour in each principal aquifer. A summary of predicted drawdown results is as follows:
 - Knobloch coal – The extent of the five foot drawdown contour was predicted in the Knobloch coal approximately 9.2 miles east of the mine area. A similar extent is expected northeast/southeast of the mine area; however, boundary condition effects in the calibrated model led to increased drawdown at the north and south boundaries in later years of mining in the transient simulation.
 - Alluvium –No drawdown of five feet or greater was predicted by the model in Otter Creek alluvium.
 - Clinker – Gradual but discernible changes in clinker water levels are predicted by the model. The maximum decline in water level predicted at C-3 was 2.2 feet. This is likely a conservative projection based on the relatively low K assigned to clinker in the model.
 - First sandstone aquifer/Flowers-Goodale coal – no drawdown of five feet or greater was predicted by the model for this hydrostratigraphic unit in the transient simulation. However, minimal drawdown (~2 to 2.5 feet) was predicted in later years of the transient simulation.
 - Deep underburden sandstone – drawdown resulting from mine dewatering was imperceptible in the model layer used to represent the deep underburden sandstone.

- River leakage into and out of the Tongue River was unaffected by transient stresses applied in the mine dewatering simulation. Predicted gains and losses of stream flow along Otter Creek were variable. The upgradient reach considered in the model was unaffected by the mine dewatering simulation. The model predicted temporary stream depletion of approximately 1.2 cfs in the reach adjacent to the mine. Gaining conditions were maintained throughout the transient simulation in downstream Reach 3; but an estimated reduction in flow to the river reached a maximum of 0.53 cfs at the end of year 2 of the mine dewatering simulation. None of the predicted influences on river gains/losses are expected to result in conditions outside of normal stream flow fluctuations observed at Otter Creek.
- Post-mining water level recovery rates were assessed in transient simulations of the groundwater flow model. Post-mine water level recovery is dependent on the properties of spoils that will replace the coal aquifer. A hydraulic conductivity of 0.25 was assigned to spoils in the base transient model; whereby, simulated water levels in the mine area recovered to pre-mine conditions in approximately 50 years. In a transient sensitivity analysis, K of the spoils was left constant with values previously assigned to coal. These values were much higher (ranging from 1.5 ft/day to 4.75 ft/day). Under these conditions, post-mine water levels recovered in between 15 to 20 years. The range of K evaluated in the model are well supported in the literature and represent reasonable estimates of post-mine conditions; thus, it is fitting to predict a conservative range of potential recovery times that is between 20 and 50 years.

7.2 POTENTIAL MODEL LIMITATIONS

Models are simulative tools that are constructed on simplifying assumptions of complex natural systems; as such, uncertainty and limitations are inherent in any modeling effort. Noted below are specific assumptions and/or sources of uncertainty that may limit the applicability of the Otter Creek Mine groundwater flow model.

- The model is parameterized by and calibrated to hydrologic field data collected during the baseline study from 2010 to 2014. As noted above, surface water flow data collected during this period may be temporally divergent from long-term hydrologic conditions at Otter Creek for the time period represented in the model.
- The spatial coverage and values of hydrologic input available for use in the model were variable. To the extent practical, heterogeneity of aquifer properties was included in the model. Areas with lower data density were parameterized by the nearest known aquifer properties.
- GHB conditions applied to the calibrated steady state model produced increased drawdown at the north and south boundaries when applied in transient simulations. The GHB parameter assignment limits the ability to predict the full extent of the five-foot drawdown contour within the model domain. This limitation is not detrimental to the overall modeling analysis because drawdown predicted at the model boundaries is consistent with the mean absolute steady state residual; drawdown predicted in the transient solution parameterized by the calibrated model is a conservative estimate; and the range of possible GHB and aquifer properties evaluated in the sensitivity analysis indicates that there are other appropriate parameter assignments that do not result in drawdown interference at the boundaries.
- Mine dewatering was simulated by the drain package using a constant drain conductance for each of the dewatering stress periods. Dewatering by drains is a more conservative representation of dewatering than will likely occur from direct pumping from open pits. While it is possible to predict reasonable dewatering rates from drain budgets in later time steps of a given stress period, exaggerated drain budgets in early time steps have the potential to influence budgets of other features in the transient model (e.g River Package budgets).
- These model results represent a generalized assessment of potential effects that is based on our current understanding of the hydrogeologic setting at the Otter Creek mine. The uncertainty of parameters that will effect transient results (spoils aquifer properties and storage coefficients of all strata) is highlighted in the

sensitivity analysis above. Results will be verified as mine development progresses.

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