ABSTRACT

A numerical ground water flow model of the Getchell Mine Site in Humboldt County, Nevada was constructed to predict ground water inflows associated with expansion of the Turquoise Ridge Mine (TQR) into the N-Zone ore-bodies. The MODFLOW-SURFACT code facilitated simulations of dewatering due to its robust solver and enhanced capability to handle de-saturation over standard MODFLOW.

The site is characterized by a complex structural, intrusive, and metamorphic history that generated compartmentalization and preferential paths of ground water flow. Secondary, fracture permeability and storage are the dominant controls on underground mine inflows. Matrix permeability and storage are very low. Fractured, near-surface Valmy basaltic rocks yielded significant flows to shaft dewatering wells, but underlying Preble and Comus rocks, hosting ore in fractures, yielded relatively little sustained flow. Faults, dikes, and sills intercepted during mining yielded short-term, high-rate inflows. These structures are commonly horizontal barriers, but vertical conduits to flow.

A complex network of drifts and stopes at various TQR mine levels was simplified with clusters of equivalent, contiguous volumes of mine openings represented by drains in the model. The drains were activated transiently to correspond to the mining sequence. The model was calibrated to measured well water levels from 1993 through 1999, and ground water inflows to the TQR from 1998 through 2001. Other stresses include dewatering wells. The calibrated model reproduces the hydraulic responses of the ground water system to the stresses, particularly the transient variation in ground water inflows to the TQR. The model can be used to estimate the number of drainage boreholes and time required to dewater ore-bodies ahead of mining.

INTRODUCTION

The Getchell Mine is located on the eastern flank of the Osgood Mountains, near Winnemucca, Nevada. Two surface mines, the Getchell Pit and North Pit, and the Getchell Main Underground Mine exploit gold mineralization associated with a major structure, the north-south trending Getchell Fault. The Turquoise Ridge Mine (TQR) exploits gold mineralization associated with fracturing along the northeast-trending Turquoise Ridge Fault and related structures. Mine expansion drift development was progressing from the TQR to the N-Zone at the time of model development. The N-Zone is a series of ore-bodies located north of the TQR. Numerical modeling was performed to develop a strategy for dewatering rock in the N-zone, and to estimate ground water inflow rates during the mine expansion and projected mine life.

HYDROGEOLOGY

Geology

Mine site geology is described by Berentsen et al. (1998). The rocks at the Getchell Mine include phyllite and marble of the Cambrian Preble and Ordovician Comus Formations, and mafic lavas, breccias, and tuffs (greenstones) of the Ordovician Valmy Formation. Dikes and sills were intruded during eruption of Valmy basaltic rocks. Regional and contact metamorphism of the rocks were accompanied by several subsequent tectonic and intrusive events, including Devonian-Mississipian folding and thrusting (Antler Orogeny), mid-Jurassic compressional folding, Cretaceous intrusion of the Osgood Mountains granodiorite stock and associated dacite plugs, dikes, and sills, and basin-and-range extension. The Getchell Fault separates the granodiorite stock from the rocks of the TQR and N-Zone mine areas. The Getchell Main Underground Mine is within the Getchell Fault zone.
The various tectonic events generated a network of intersecting high-angle structures, including N15W faults parallel to the Getchell Fault, and N60W, N35W, and N30E faults. High-grade ore occurrences at the TQR and in the N-Zone are associated with these structural intersections. Many of the dacite and granodiorite dikes were intruded into the northeast and northwest fracture systems throughout the area.

**TQR and N-Zone Hydrogeology**

Ground water flowed across the mine area from the Osgood Mountains on the west toward the valley to the east prior to mining. The Getchell Fault is believed to be a leaky barrier to ground water flow.

Ground water recharge to the mine area is derived partly from infiltration of incident precipitation. This recharge is estimated to be 10 percent of the average annual precipitation of about 12 inches, contributing about 135 gpm to the modeled area. Additional recharge of about 180 gpm is derived from leakage across the Getchell Fault and/or runoff from the upslope areas, infiltrating at the break in topographic slope east of the fault.

Ground water storage is the principal component of the mine area water balance under mining conditions. Ground water inflow from storage to the mine, which increased to about 800 gpm by June 2001, exceeds the recharge rate.

The occurrence of ground water is structurally compartmentalized. Faults, dikes, and sills intercepted during mining yielded short-term, high-rate inflows. These structures are commonly horizontal barriers, but vertical conduits to flow. Secondary, fracture permeability and storage are the dominant controls on underground mine inflows. Matrix permeability and storage are very low.

The near-surface Valmy basaltic rocks are highly fractured. Permeability testing indicated hydraulic conductivity in the range of $10^{-4}$ to $10^{-3}$ cm/sec. Initial production rates from dewatering wells exceeded 1,400 gpm. The underlying Comus and Preble Formation rocks yield relatively little sustained flow. Permeability testing of dewatering wells indicated hydraulic conductivity of $10^{-6}$ to $10^{-3}$ cm/sec, decreasing with depth. Flow rates ranged from 60 to 135 gpm. Pre-mining water levels indicated strong downward vertical gradients between the Valmy and the Comus and Preble Formations (150 – 180 foot head differences), and over 700 feet of head loss to a depth of about 3,000 feet.

**N-ZONE MINING AND DEWATERING PLANS**

N-Zone mining plans included access via two northerly-trending drifts known as the Hanging Wall Decline and the Main Access Decline. Both drifts originate at the TQR shaft area, and will be located above and below the ore-bodies. Access ramps and drifts will be driven to reach the ore zones.

The ore zones are incompetent rock, which is prone to failure. Depressurization and drainage of these areas is critical for safe and efficient mining. Dewatering the N-Zone ore-bodies would be accomplished by drilling drainage boreholes from access drifts into the stope blocks before mining. Drainage boreholes would be drilled in fans about three months after access drifts to individual stopes are completed.

**MODEL DEVELOPMENT**

Objectives in developing a ground water flow model for the TQR and N-Zone areas included: 1) Calibration of the model within the conceptual framework of mine hydrogeology, including reproducing measured ground water inflows; 2) Developing a strategy for timely dewatering that minimizes duration to support a planned 2,500 tons/day mine; and 3) Estimation of the timing and range of ground water inflows into the N-Zone over the projected mine life.

MODFLOW-SURFACT 99, Version 2.1 (HydroGeoLogic Inc., 1999), was used for the ground water flow modeling. This enhanced version of MODFLOW does not convert de-saturated cells to no-flow cells. The robust and efficient PCG4 solver, and sub-routine employing Newton-Raphson linearization with backtracking, facilitated convergence.
Model Domain and Configuration

The model domain encompasses the Getchell Pit, the North Pit, the Getchell Main Underground Mine, the Turquoise Ridge Pit, the TQR, and the N-Zone. The western, up-gradient boundary of the active model domain is defined by the Getchell Fault. Elevated recharge is simulated along the Getchell Fault, relative to recharge over the rest of the model domain, representing leakage of ground water across the fault and/or recharge from runoff at the break in topographic slope. The northern and southern edges of the model domain are approximately parallel to the regional direction of groundwater flow, and boundary conditions are no-flow. Constant hydraulic heads define the eastern, down-gradient boundary. These boundary conditions are supported by data indicating that hydraulic barrier effects of faults throughout the area limit the zone of influence of mine dewatering to the modeled area. The eastern constant head cells impose the observed downward hydraulic head gradient within the mine area.

Drain cells represent the effects of TQR and N-Zone underground mine workings, including drifts, ramps, and stopes, and the Getchell Pit. The pit drains were used to approximate effects of early dewatering wells, which have a poorly-documented history. Later pit and TQR shaft dewatering wells were simulated with “fracture wells” (HydroGeoLogic Inc., 1999). These wells provided important constraints on model calibration through their capability of reducing the specified extraction rate, if not sustainable.

The model grid cells range in size from 62.5 x 62.5 feet in the TQR and N-Zone areas to 250 x 250 feet in areas distant from the mines. The model consists of 23 layers, ranging in thickness from over 1,000 feet for the Valmy Formation to 15 feet for simulating mine access drifts. The vertical extent of the model domain ranges from the ground surface (5,300-5,400 feet amsl) to 2,100 feet amsl, well below all existing and planned mine workings.

The modeled distribution of hydrogeologic units is based on surface geology and the mine geologic block model. Fault zones were simulated as separate hydrogeologic units, with values of hydraulic conductivity that generally impede the horizontal flow of ground water.

Simulation of the Effects of Drifts and Ore-Bodies

Drift and ramp drain elevations correspond to the bottoms of the mine openings. The drain elevations of dewatered TQR ore-bodies were given the elevations of the access drifts from which the ore-bodies were presumably drained. Due to uncertainty regarding the dewatering effort in the TQR, the conductance of the ore-body drains was a calibration variable. Drain activations correspond to the timing of development of the mine workings.

The mine development sequence and the history of ground water inflow to the TQR were critical components of the model calibration. Ground water inflow increased from about 300 gpm to about 800 gpm from January 1998 to June 2001 as the shafts were completed, the various levels were developed and mined, and excavation of drifts toward the N-Zone was begun. Complex networks of mine openings, many smaller than grid cells, were simplified by summing the plan-view areas of drifts and stopes, where clusters of workings exist at each mine level, and condensing the aggregate areas to centered contiguous areas. Drain cells, representing the volumes of aggregate workings, were placed at the centers of the actual clusters.

N-Zone drain cells, simulating projected mine infrastructure and stopes, were located and activated according to mining plans. Ore-bodies will be dewatered by drainage boreholes, drilled from adjacent and underlying access drifts. Inflows from ore-body dewatering will be directly proportional, and dewatering time will be inversely proportional, to the number of drainage boreholes. Drainage boreholes were simulated using drain cells with a calculated conductance that reflects the number of boreholes required to dewater an ore zone. Drain elevations for simulating ore-body dewatering were set at the floor elevations of the respective access drifts. The drain activation for ore-bodies lags the drift development by three months, the delay for drainage borehole drill crews to obtain access.
The modeled conductance of the N-Zone ore-body drains is proportional to the sum of the areas of the walls of all drainage boreholes in an ore-body. Using the approximate size and shape of each ore-body, the number of drill holes required to dewater each ore-body was calculated, assuming that fans will be drilled at 100-foot intervals along the drifts, with 5 to 6 holes per fan (TRC, 2000). Each hole was assumed to penetrate the entire thickness of the ore-body. The product of the sum of the borehole wall areas and the modeled hydraulic conductivity (day\(^{-1}\), rate/unit thickness) of the ore-body, divided by the number of drain cells representing the ore-body, equals the conductance of individual drain cells.

**MODEL CALIBRATION**

The model was calibrated under “steady-state” and transient conditions. The approximate “steady-state” condition corresponds to measured water levels before renewed Getchell Pit dewatering in 1993. The transient calibration simulation extends from February 1993 through July 2001, and includes Getchell Pit and TQR dewatering wells, and ground water inflows to the TQR.

Calibration of the model was constrained by aquifer test hydraulic conductivity values and literature values of hydraulic conductivity, anisotropy, and storage. The well extraction rates and drain activations were allocated to 44 stress periods, in which the time-averaged rates for each period were simulated.

Figure 1 shows a plot of observed and simulated heads for steady-state conditions. Steady-state target locations (monitoring well screens) span the entire depth range of the model (layers 1 through 23), and target heads reflect the downward vertical gradient. The ME is –6.1 feet, the MAE is 30.7 feet, and the RMSE is 36.4 feet. The total range in observed head is 718 feet, and the RMSE/\(\Delta h\) is 5.1 percent.

The model is also calibrated to transient well water levels from 1993 through 1999 (Figure 2), and ground water inflows to the TQR from 1998 through 2001 (Figure 3). The transient targets also span the entire depth range of the model. The ME is –18.6 feet, the MAE is 87.4 feet, and the RMSE is 157.4 feet. The total range in observed head is 1,556 feet, and the RMSE/\(\Delta h\) is 10.1 percent, indicating the errors are small relative to the head loss in the model domain.

**Figure 1.**

All measured water levels were given equal, 100% weighting in the statistical calculations. The weighting is extremely conservative, because many measurements were made in open holes (not screened at specific depth intervals). The open-hole measurements were assumed to reflect the head in the Valmy Formation (targets were placed in layer 1). This assumption is not necessarily correct under steady-state conditions due to downward vertical gradients, and particularly problematic under transient conditions, with deep-seated stresses of the underground mine affecting measured water levels. The statistical measures of calibration are acceptable, in spite of inclusion of some large, unweighted calibration errors.
The simulated transient hydraulic heads approximate the observed effects of the Getchell Pit, dewatering well pumping, and ground water inflows to the TQR. Simulated ground water inflows are very similar to the recorded ground water inflows. This “match”, in conjunction with the general agreement between observed and simulated heads at most targets (both steady-state and transient), indicates that the model is a good approximation of the hydrogeology at the mine site.

Figure 3.

**PREDICTIONS OF N-ZONE MINE INFLOW**

Future ground water inflows to the existing TQR workings, and to planned N-Zone development drifts and stopes, were estimated with the calibrated model. The model also provided an estimate of the number of drainage boreholes and time required to effectively dewater ore-bodies in the N-Zone. (Note that mining operations were indefinitely suspended in 2002).

The numerical model can provide estimates of sustainable ground water inflow to the mine. The model cannot predict potential large, relatively short-term inflows that originate from fracture zones.

The mine inflow was predicted to increase from about 800 gpm in August 2002 to about 1,650 gpm in 2003 and 2004, as development of N-Zone mine infrastructure and dewatering of the ore zones were simulated. Mining rates were to be maximized after 2004, with exploitation of all ore zones. Inflow was predicted to steadily decline after 2004, to about 850 gpm in 2014.

The model is very sensitive to hydraulic conductivity and confined storage of the Comus and Preble Formations. Significant deviations from the observed inflows, and large ranges in estimated future mine inflows were simulated for 50% and 200% of the calibrated hydraulic conductivity, and for half-order variations of the calibrated confined storage. Predicted maximum inflows range from 1,300 to 2,100 gpm for the hydraulic conductivity variations, and 1,000 to 2,150 gpm for the storage variations.

The model indicates that dewatering of individual ore zones can be accomplished within approximately three months of the installation of all drainage boreholes in a given zone. This estimate was determined from the modeled head decline in drain cells representing the ore zones. Dewatering is complete when the head is equal to the elevation of the drains.

**CONCLUSIONS**

The enhancements of the MODFLOW-SURFACT code facilitated simulations of underground mine dewatering. The calibrated model reproduces the hydraulic responses of the ground water system to the stresses, particularly the transient variation in ground water inflows to the TQR. Sensitivity analysis demonstrates the narrow range of permissible hydraulic property values, reinforcing the reliability of the calibrated model for predictions. The model can be used to predict future ground water inflows, and the number of drainage boreholes and time required to dewater ore-bodies ahead of mining.

**REFERENCES**

