Hydrogeologic Characterization and Numerical Modeling of Groundwater Inflow to Support Feasibility Studies for Underground Mining – a Case Study in the Southeast Idaho Phosphate District

Brent Everett[1], Scott Effner[1], Jon Kaminsky[1], David Kramer[2]

[1]*Whetstone Associates, 104 W. Ruby Avenue, Gunnison, Colorado, USA, beverett@whetstone-associates.com, seffner@whetstone-associates.com, jkaminsky@whetstone-associates.com,*
[2]*Paris Hills Agricom, Inc., 9 N. Main St., Paris, Idaho, USA, dkramer@parishills.com*

Abstract Reliable characterization of groundwater inflow and water quality is a critical component of feasibility studies for underground mines. Prediction of inflow volumes, timing, and location are required to support mine design and cost estimates. Water quality and disposal issues often affect mine economics and permitting strategies. The following paper presents an overview of hydrogeologic issues relevant to mine planning and a case study of the hydrogeologic investigation and inflow analysis that was prepared to support the feasibility study for the Paris Hills Underground Phosphate Project.

Keywords mining hydrology, inflow prediction, groundwater modeling, mine planning

Introduction

Preparation of a successful feasibility study is a key milestone in the development of new underground mines. Feasibility studies are often required to obtain financing from outside investors. They also provide mine planning information and analysis of the economic viability of the project. Mine dewatering and environmental issues related to disposal of pumped water can be significant costs. The dewatering approach, volume of discharge, and timing of capitalization for pumping systems are all important considerations for the economic analysis. Environmental concerns such as impacts to water quality or decreases in groundwater levels and availability may also affect the project's ability to obtain required permits.

Given the potential importance of groundwater issues to the viability of a new underground mine, hydrogeologic characterization should start at an early stage in project development. If possible, the investigation should be incorporated into the mineral exploration drilling program to minimize costs. Early data collection allows for a phased approach to the investigation which can be adapted with increased understanding of the groundwater system. The following paper discusses the types of hydrogeologic data required to support feasibility studies and provides recommendations for a phased testing approach. It also presents a case study of the hydrogeologic investigation and numerical groundwater model for the Paris Hills Underground Phosphate Project.

General Approach to Feasibility–Level Hydrogeologic Investigation

The first phase of hydrogeologic investigation to support feasibility studies for new underground mines should begin during the earliest phases of mineral exploration drilling. Data including depth to water, air-lift discharge, losses in circulation, and field water quality parameters for pH, specific conductance, and temperature are easily recorded by exploration crews and provide the first indication of groundwater issues that may become significant cost and regulatory considerations for the future mine. As confidence in the grade and extent of mineralization increases, a formal groundwater investigation should be initiated. The timing of the investigation should coincide with the final phase of delineation drilling to provide access to boreholes that are spatially distributed across the deposit and intersect significant structural or stratigraphic features. The focus of work is to collect hydraulic conductivity and water level data that will be used to support the preliminary mine design and dewatering analysis. Water chemistry data should also be collected to evaluate environmental issues associated with dewatering discharge.

Several practical approaches exist to collect hydraulic conductivity and water level data in uncased exploration boreholes. Packer permeability tests can be used in consolidated formations. There are a number of testing methods, but generally, the tests are performed by pumping water into or out of a section of borehole that has been isolated using an inflatable packer or pair of packers. The flow rate, injection pressure, and water level recovery data are used to calculate the hydraulic conductivity of the isolated interval. Shut-in water levels also provide valuable information that can be used to calculate vertical gradients and pressure heads on hydrologically significant features (*e.g.* faults, permeable beds, aquitards). Packer tests can be performed in cored or air-rotary boreholes using upstage or downstage testing methods. The downstage method interrupts drilling and uses a single packer to test the bottom of the hole as it is advanced. The upstage method uses two packers to isolate sections of the borehole after it has been drilled to the total depth. Selection of the testing approach depends on consideration of variables such as formation stability, drilling method, depth of testing, and depth to water.

Packer tests typically have short duration (15 to 20 min) and relatively small radii of influence. It is therefore important to perform a statistically significant number of tests to develop adequate confidence to extrapolate the calculated hydraulic conductivity values to the larger rock mass. Packer testing should target competent and fractured rock as well as structural and stratigraphic zones of interest.

Vibrating wire piezometers (VWPs) can also be used to provide targeted groundwater level data during delineation drilling. The instruments measure pore pressure by sensing changes in the vibrational frequency of a wire stretched between a fixed anchor and a diaphragm. Multiple VWPs can be installed in a single borehole to evaluate stratified aquifers or different zones of interest. VWPs are permanent installations that are grouted in place during borehole abandonment. As such, they have the added advantage of being able to monitor dewatering progress as the mine is put into production.

Airlift pumping tests are another method that can be used to evaluate hydraulic conductivity in stable exploration boreholes. The tests may be performed at any point during drilling with an air-rotary rig and favorable water level configuration. Drilling is stopped with the bit near the bottom of the hole and the rig compressor is used to airlift water to the surface. Discharge and water level recovery data are collected and used to estimate hydraulic conductivity. Airlift tests have significant limitations in that the data are often difficult to interpret because of multiple productive zones or lost circulation. The volume of annular space, depth to water, and percent submergence of the air turnaround point are additional variables that affect the efficiency of pumping. Water may not return to the surface in boreholes with deep water levels and low submergence of the turnaround point.

In addition to providing an opportunity for cost-effective measurement of hydraulic conductivity and water levels in open boreholes, mineral exploration drilling programs provide the basic stratigraphic and structural data that are required to develop the conceptual hydrogeologic model (CHM). The CHM is a working understanding of the patterns of groundwater flow, depth of mining submergence, and relative hydraulic conductivity of structural and stratigraphic features that have potential to provide groundwater inflow to the underground workings. The CHM is continually updated as new information becomes available.

A second phase of hydrogeologic investigation may be required near the end of the exploration program if the project is viable and initial data indicate significant potential for groundwater inflow. Indicators of inflow hazard include the depth of mining below the regional groundwater level and proximity of the planned workings to surface water, permeable strata, and water bearing structures. At this point, the mine plan is better defined and areas of potential high inflow can be targeted for additional testing. The second phase of investigation should also include installation of monitoring wells to develop water quality data that can be used to estimate costs associated with treatment and disposal of dewatering discharge. Water disposal issues can trigger permitting requirements that affect the project schedule.

Depending on the importance of groundwater issues, the level of confidence in the CHM, and the available budget, a multi-well aquifer test may be warranted prior to preparation of the feasibility study. Aquifer tests are expensive, but provide high confidence data for large rock masses if designed and performed correctly. Design considerations are site-specific, but at a minimum the tests should provide transmissivity and storage data for the hydrogeologic unit of interest. Aquifer tests can also provide information about compartmentalization of the aquifer, anisotropy of drawdown, hydraulically active structures, and water availability to drive sustained groundwater inflow.

At the end of the second phase of testing, hydrogeologic data should be sufficient to support a feasibility-level dewatering design and estimate of mine discharge. The CHM and dewatering analysis will typically have substantial uncertainty, but should be adequately conservative to ensure that potential dewatering costs do not make the project unviable. A general rule to follow is that feasibility-level cost estimates should have an accuracy of at least ± 20 % (Lowrie 2002). This level of accuracy usually requires development of a numerical model for all but the simplest of mining plans and hydrogeologic environments.

Case Study- Paris Hills Project

The Paris Hills Underground Phosphate Project is being developed by Paris Hills Agricom, Inc. (PHA) in Bear Lake County, Idaho. The project will recover stratiform phosphate ore from the Meade Peak Member of the Permian-age Phosphoria Formation using room and pillar mining methods followed by retreat mining with an average 60 % pillar extraction and subsidence of the overlying strata. Entry and crosscut dimensions will be 5.25 m wide with a minimum height of 1.65 m (1.5 m with 0.15 m out of seam dilution). The entries are laid out quartering the plunge of the horizontal limb to provide an apparent dip of about 12.5°. Mining will be by continuous miners and the depth of the workings will increase from the surface at the south portal down to about 900 m below ground surface (bgs) at the northern extent of the mine.

The CHM for Paris Hills includes upper and lower flow systems separated by a leaky aquitard. The upper flow system includes the Rex Chert member of the Phosphoria Formation and overlying strata such as the Dinwoody Formation and Thaynes Limestone. It is recharged by infiltration of precipitation, flows to the northwest, and may be semi-confined to confined depending on location. The lower flow system is part of a regional-scale limestone aquifer that occurs in the Wells Formation. Groundwater in the lower flow system is confined and flows northwest roughly parallel to the plunge of the synclinal fold that contains the ore deposit. The Meade Peak is a leaky aquitard that separates the two flow systems. The submergence of the mining horizon increases to the northwest. The elevation of the portal will be 30 to 50 m above the water table. The northwestern extent of the underground workings will be submerged by more than 700 m.

Groundwater flow is affected by structural features in the mine area. Increased fracturing along the axis of the associated syncline appears to exert controlling influence over the flow direction with groundwater flowing northwest into the hinge. The Consolidated Fault Zone also exerts local control over the direction of groundwater flow with potentiometric surface lines for both the Rex Chert and Wells Formation bending into the structure. Increased hydraulic conductivity is also likely to be associated with other faults in the project area. The Paris Thrust Fault is a large displacement fault located west of the planned mine. It places lower Cambrian-age rocks over younger Paleozoic sedimentary strata and is conceptualized to act as a barrier to groundwater flow.

The hydrogeologic investigation for the feasibility study was developed using a phased approach. Initial exploration was accomplished using air rotary drilling to pre-collar the holes to a point above the Meade Peak Member. Delineation of the ore body was performed using HQ- and PQ-diameter core drilling. Because of issues with lost circulation and the depth to groundwater which typically exceeds 200 m, little hydrogeologic data were available from the initial exploration drilling program.

The first phase of hydrogeologic investigation for the site began in 2011 and consisted of packer testing in cored mineral exploration boreholes and installation of VWPs in known aquifers above and below the mining horizon. The packer tests used a downstage method with a wireline packer assembly. The program experienced significant technical challenges because of the depth of testing which often exceeded 700 to 800 m. The high inflation pressures required to properly seat the packers deformed the rubber elements making retrieval through the core bit at the end of testing difficult. However, a total of 21 packer tests were successfully completed using the USBR step injection method (O’Rourke *et al.* 1977). Calculated hydraulic conductivities ranged from 2.8×10^{-5} m/d to 1.3×10^{-1} m/d. Measured water levels for the shut-in sections indicate that portions of the ore body will be submerged below the regional base level by more than 700 m.

Paired VWPs were also installed in eight boreholes to monitor water levels in aquifer units above and below the mining horizon. The upper flow system is separated from the mining horizon by approximately 60 m of low permeable shale. The lower regional aquifer is located 1 to 3 m below the floor of the mine and is separated from the planned underground workings by a thin mudstone bed at the base of the Meade Peak. VWP data confirmed groundwater depths in the upper and lower aquifers and were used to document a northwest groundwater flow direction.

The second phase of hydrogeologic investigation included installation and testing of eight monitoring wells. Three wells were installed in the lower aquifer and one in the upper aquifer to evaluate the chemical characteristics of the planned dewatering discharge. Two wells were installed in a perched zone near the toe of the planned waste rock dump to provide baseline data for permitting, and two wells were installed to monitor water quality in the area that is being considered for reinjection of the dewatering discharge. Pneumatic slug tests in the monitoring wells returned hydraulic conductivity values between 4.6 m/d and 16.4 m/d for the lower regional aquifer and 3.2 m/d for the upper aquifer.

The results of the hydrogeologic investigation were used with regional data to develop numerical simulation of mine dewatering in MODFLOW-SURFACT version 3.0 (HydroGeologic 2001). The groundwater model was prepared in two parts: an initial steady-state model to simulate the pre-mining groundwater flow system and a transient model to simulate time-dependent dewatering as a func-

Zone		Effect	Extent	Characteristics
Caved Zone		**Increased Vertical and Horizontal Transmissivity** intersected groundwater quickly drained into mine	6 to 10 times the height of the mining horizon	Zone of complete stratigraphic disruption. Extends 6 to 10 times the mining height above the workings. Roof strata collapse into the opening and form rotated blocks with increased volume that limits the upward progression of caving. Groundwater intersected by the caved zone is quickly drained into the mine.
Fractured Zone		**Increased Vertical Transmissivity** Potential for increased seepage from overlying units	Top of caved zone to a maximum height of about 24 to 30 times the mining thickness	Zone of vertically transmissive fractures without rotation. Bedding retains original attitude and does not fall or detach. Fracture density and permeability increase downward. The combined height of the fractured and caved zones can be 24 to 30 times the mining height. Increased vertical and horizontal permeability allow for drainage of intersected water into the mine workings.
Continuous Zone	Dilated Zone	**Increased Storage** Potential for temporary local decrease in water levels to fill additional storage volume	Top of fractured zone to a maximum height of about 60 times the mining thickness	Zone of beam deformation in which strata sag but do not form vertically connected fractures. Bed dilation increases groundwater storage but does not allow for vertical transmission of water into underlying zones. Generally extends about 24 to 60 times the mining height above the workings. Wells and surface water intersected by the dilated zone will experience temporary reductions in level/volume as water goes into storage.
	Constrained Zone	**No Change** Potential for hydrologic impacts is minimized	Top of the dilated zone to 15 m below ground surface	Zone of no significant effect on transmissivity and storage. Strata are affected by subsidence but are not sufficiently deformed or strained to dilate and significantly increase storage. Overall extensile strains remain less than 0.1 %, the point at which rock masses are not sufficiently disrupted to increase permeability.
	Surface Fracture Zone	**Increased Transmissivity** Potential for localized, short-duration changes in groundwater levels	0 to 15 m below ground surface	Surface zone with shallow tension fractures caused by subsidence. Fractures generally extend less than 15 m below ground surface and are spatially related to panel/trough edges and areas of local extension. Changes in shallow hydraulic regimes are short lived because fractures are localized and quickly filled by sediment.

Table 1 *Hydrologic effects of mining subsidence (Kendorski 1993).*

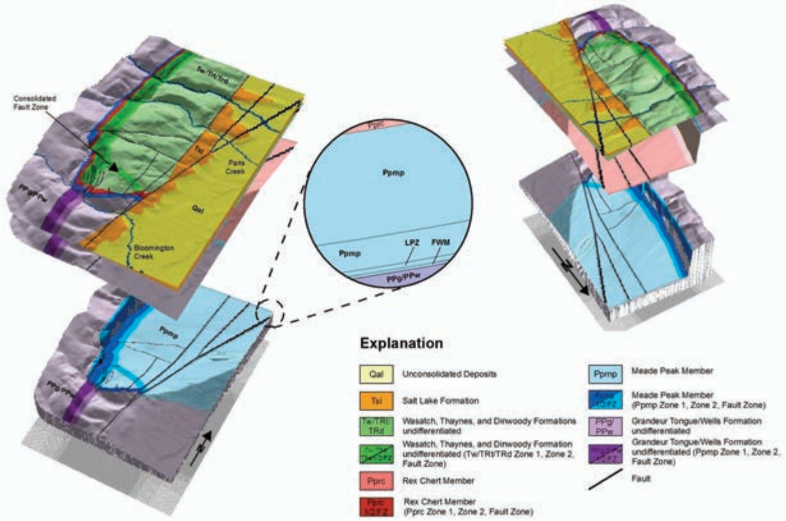

Fig. 1 *Three dimensional diagram of model domain.*

tion of mine development. The model includes representations of the upper and lower aquifers, the leaky aquitard formed by Meade Peak, and structural features such as folds and faults that influence groundwater flow. Hydrogeologic changes from subsidence during retreat mining are simulated according to the conceptual model in Table 1.

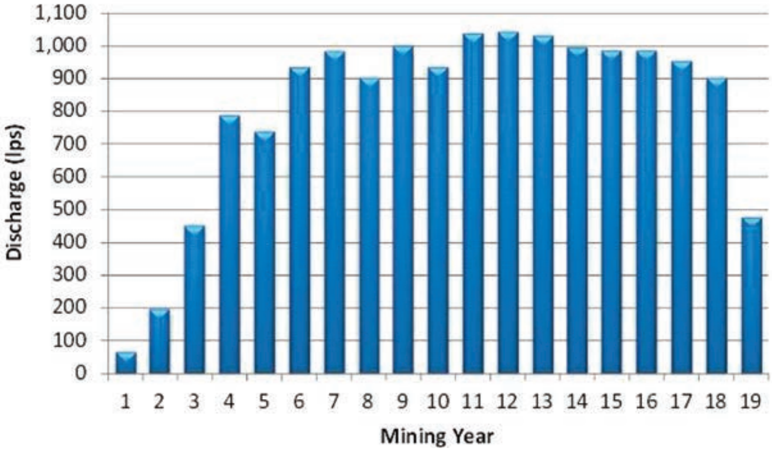

Fig. 2 *Predicted average annual pumping rates for mine dewatering.*

The flow field for the steady-state groundwater model was calibrated using water level data from VWPs. Dewatering of the underground workings was simulated using 17 wells to intercept groundwater before it enters the mine. Some groundwater will bypass the well field and report to the underground workings. Discharge from the mine was simulated using drain cells that start near the portal and move northward with mine development. Subsidence from retreat mining was simulated by increasing vertical and horizontal hydraulic conductivity in the caved zone and vertical hydraulic conductivity in the fractured zone. Hydrologic changes in the continuous zone are not expected to influence mine dewatering and were not modeled. A diagrammatic representation of the numerical model is shown in Fig. 1. The predicted average annual dewatering requirement for the mine is shown in Fig. 2.

Conclusions

Hydrogeologic characterization should start during the initial stages of project development for underground mines. Groundwater issues often affect the viability of new mining projects and reliable hydraulic conductivity, water level, and water quality data are needed to support mine planning. Early data collection allows for a phased hydrogeologic investigation that can be adapted to site-specific conditions as understanding of the groundwater system increases. This approach was used to support the feasibility study for the Paris Hills Underground Phosphate Project. PHA completed a successful feasibility study for the Paris Hills Underground Phosphate Project in December 2012, and is on track to start production in 2014.

Acknowledgements

We thank Paris Hills Agricom, Inc. for their assistance with this paper and for allowing us to present the results of the dewatering analysis for their project.

References

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

Kendorski FS (1993) Effect of high-extraction coal mining on surface and ground waters. 12th Conference on Ground Control in Mining, West Virginia University

Lowrie RL (2002) SME Mining Reference Handbook, p. 1

O'Rourke JE, Essex RJ, and Ranson BK (1977) Field permeability test methods with applications to solution mining. U.S. Bureau of Mines Report BuMines °FR, p. 180