Mine Dewatering in a Compartmentalized Hydrogeologic Setting at Sishen Mine in South Africa

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Abstract Sishen mine in South Africa is one of the largest open-pit iron mines in the world. It is characterized by a complex, compartmentalized hydrogeologic setting that comprises numerous dykes, regional water-bearing faults, and inter-bedded localized geologic units. The groundwater flow in the vicinity of Sishen mine is mainly controlled by regional dykes and faults in a karst aquifer. A 3-D finite-element groundwater flow model using MINEDW™ was constructed to simulate the unique geologic setting for effective mine-water management and dewatering planning at the mine.

Keywords compartmentalized, dykes, faults, flow model, rainfall, dewatering, MINEDW

Introduction

Sishen mine’s complex, compartmentalized hydrogeologic setting, along with irregular shapes in the open-cast pit configuration, the formation of swallets (similar to sink holes) in the riverbed, and large sporadic torrential rainfall events in South Africa, pose significant challenges for effective mine-water management and dewatering planning at the mine. Dry mining conditions are necessary to ensure stability of slopes, optimize mine production, and minimize costs.

A conceptual model was developed to assess the regional hydrogeologic setting before and during the course of mining. The conceptual model integrated the collected data to produce an accurate representation of the geologic and hydrogeologic setting and is continually being refined as new hydrogeologic information becomes available.

Development of a 3-D finite element groundwater flow model using MINEDW™ is considered to be one of the key components of the mine-water management strategy. The aim of the model is to accurately predict mine dewatering rates by integrating the conceptual model with site characterization data, the mining development plan, and the mine closure plan. The numerical model is designed to:

- predict dewatering requirements that must be implemented to manage water levels to ensure ’dry’ conditions;
- identify data gaps in the conceptual model;
- scope out targeting hydrogeologic investigations to improve the confidence level of the model results;
- expand the groundwater monitoring system;
- assess uncertainties related to future dewatering scenarios;
- predict the areal extent of influence due to dewatering and the impact of mining activities on the water demands of stakeholders. Given that several mines have been operating in the catchment area, a robust groundwater flow model is critical

to simulate the hydrogeologic impacts attributable to different mines; and
- predict post-mining conditions after mining has ceased.

Current Dewatering Status

The pit area is approximately 14 km in length and 4 km wide and consists of a number of individual pits (fig. 1). Currently the deepest mining level is at 270 m below ground surface and by 2030, this level will reach 400 m below ground surface. Numerous diabase dykes and faults are encountered in the mining area. The nature of these regional structures will be discussed in the following sections.

Dewatering at Sishen mine is effectively achieved by pumping continuously from a series of dewatering wells in and around the pit. Surface water from rainfall events is removed by the installation of mobile pumps in sumps on the mine floor and pumping this water to the surface. Currently 19 dewatering wells, with a total abstraction rate of approximately 1500 m^3/hr, are in operation to maintain 'dry' working conditions in the different pit areas.

Water exploration wells are continuously being drilled and developed into dewatering wells to lower water levels below mining levels. Due to the pit configuration and mining operations, this practice is becoming more challenging. In the deepest pit, depicted in fig. 2, measured water levels are currently very close to the pit bottom.

Due to the complex hydrogeologic setting and pit configuration of the mine, a high confidence level, calibrated 3-D groundwater model that can incorporate flow through fractures is required to predict future dewatering rates to maintain 'dry' working conditions, which are crucial input to determine engineering and infrastructure requirements to discharge mine water.

Geologic Setting and Conceptual Hydrogeologic Model

The Sishen iron ore deposit is situated on a major domal structure which is defined by a basal carbonate platform sequence termed the Campbellrand Subgroup and the overlying iron-formation of the Asbesheuwels Subgroup. This carbonate sequence, which is the oldest lithostratigraphic unit, forms the basement rock and is considered as having high storage potential for groundwater.

A siliceous, residual breccia (Chert in fig.3) unconformably overlies the carbonates and is thought to have developed on an irregular karst surface as a possible residual solution collapse breccia. Due to the brecciated nature of this Chert formation, it is considered to act

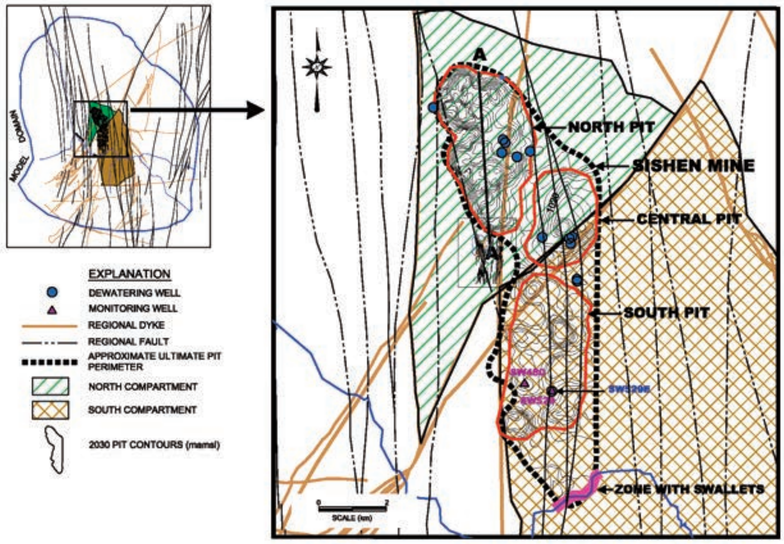

***Fig. 1** Sishen Pit Configuration, Dewatering Wells, and Hydraulic Compartments*

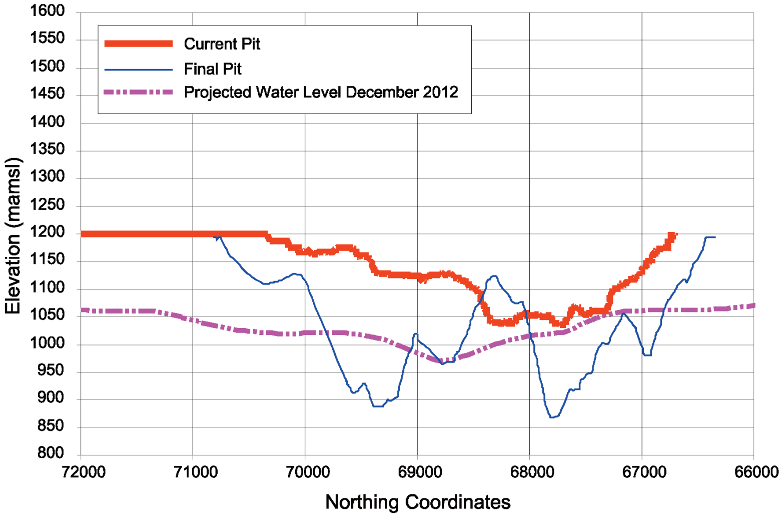

Fig. ***2*** *Current and Future Pit Bottom Elevations and Current Water Levels Along Section A-A'*

as an important pathway for groundwater. A number of high yielding water strikes have been encountered in this formation during drilling.

Folded banded ironstones (BIF in fig. 3) overlie the Chert breccia with laminated hematite ore forming the top part of this unit. This unit is highly fractured and considered as having a high hydraulic conductivity (*K*).

The BIF is overlain by conglomerate and shales (Gamagara and quartzite in fig. 3) that grade upward into a purple hematite rich, fine-grained quartzite. This unit generally has low K and low storage coefficient.

Along the western side of the mine area, lava (lava in fig. 3) has been thrust over the shales and quartzite alongside a 9 to 11° thrust plane. The top part of the lava is highly weathered and is considered as having higher K than the lower parts. Groundwater flow in the lava is generally restricted to faults and dyke zones that are encountered in the unit.

The regional area has been subjected to intensive structural deformation in the form of folding, thrusting and faulting or fracturing. Easterly directed crustal compression led to the development of large-scale regional north-south trending folds. These prominent north-south striking, moderately (60° to 70°) westerly dipping, normal faults occur in the area and represent deformation zones. A number of dewatering wells are within the permeable faults and the permeable bands associated with the dykes, and relatively high pumping

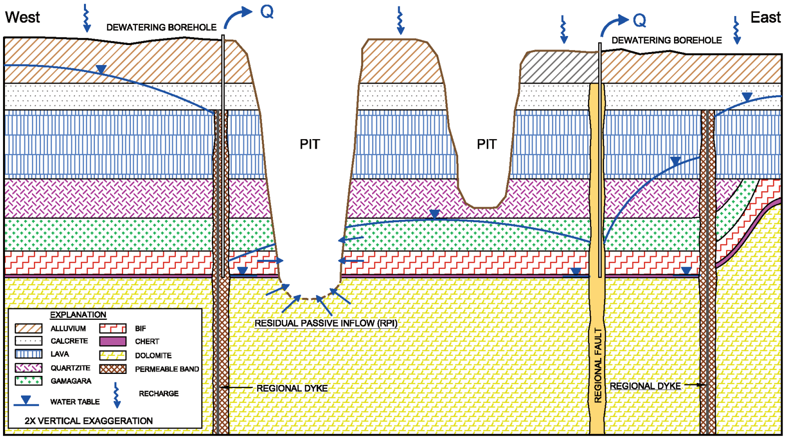

Fig. ***3*** *Geologic and Hydrogeologic Settings of Sishen Mine* rates can be sustained from these water-bearing zones.

In the pit area a number of prominent diabase dykes with very low K are present and form impervious barriers that compartmentalize the groundwater (fig. 1).

Tertiary clay, calcrete and Aeolian sand of the Kalahari Formation cover a large part of the area and are on average approximately 50 m thick in the vicinity of Sishen mine. The clay below the calcrete and sand acts as an impermeable zone and a shallow aquifer is present in the Kalahari Formation.

Swallets have been observed in the site area, the largest of which was formed in the channel of the Gamagara River (figs. 1 and 2) to the south of the mine area (Meyer 2009; PHD 2007). A major karstic feature was also encountered in the southern part of the mine (Mc Gavigan 2009). It is unlikely that the swallets in the Gamagara River would have an impact on dewatering during the dry season; but following intense rainfalls, the runoff to the swallets could, over short periods of time, locally affect groundwater conditions. For example, on 2 May 2008, a rainfall of approximately 86 mm/d was recorded in the mine vicinity. Such a large storm event could introduce a large amount of recharge to the groundwater system through the swallets. Swallets will be simulated in the model update to assess the effect they have on the predicted dewatering requirements.

Description of Numerical Groundwater Flow Model

The numerical groundwater flow model constructed for this investigation utilizes the 3-D numerical code, MINEDW™ (Azrag *et al.* 1998), developed by Itasca, which solves groundwater flow problems with an unconfined (or phreatic) surface and confined aquifers using the finite-element method. MINEDW™ has several attributes that were specially developed to address conditions often encountered in mine dewatering. This modeling code is internationally recognized and has been used and verified at numerous mine dewatering projects throughout the world.

The model domain shown in figs. 1 and 4 is approximately 45 km along the west-east direction and 60 km along the north-south direction. The area of the model domain is approximately 3,000 km^2. The numerical model comprises 159,475 nodes and 288,764 elements. The finite-element mesh configuration and the simulated geologic units in the vicinity of pit, which encompasses about one-tenth of the entire model domain, are depicted in fig. 4. The finite-element discretization is finest in the areas where dewatering wells are clustered with horizontal dimensions of less than 10 m (fig. 4). The size of the mesh then gradually increases toward the boundaries of the model with a distance of approximately 3.5 km between adjacent nodes at the edge of the model. The structures as shown in fig. 1 are simulated in the model with a finely-discretized element as indicated in fig. 4.

Ten model layers were used to simulate the pit areas and the detailed geologic units to the west of the pits. To the east, there are seven model layers. This difference in layering, which is made possible with the pinch-out capability of MINEDW™, represents the absence of some of the geologic units to the east of the pit (and also reduces the computational requirements of the model). The groundwater flow model incorporates all geologic settings as depicted in fig. 3. The total thickness of the model is approximately 1,200 m with the bottom of the model being 800 m below the final pit bottom.

The first two layers of the northern and southern model boundaries were assigned with constant-head boundary conditions. The bottom of the model was assigned with no-flow boundary conditions. The variable-flux boundary condition, a special feature of MINEDW™ that enables an essentially infinite groundwater flow system to be simulated at the model boundaries, was assigned to the western and eastern lateral boundaries of the model. The recharge is simulated with a time-varying value.

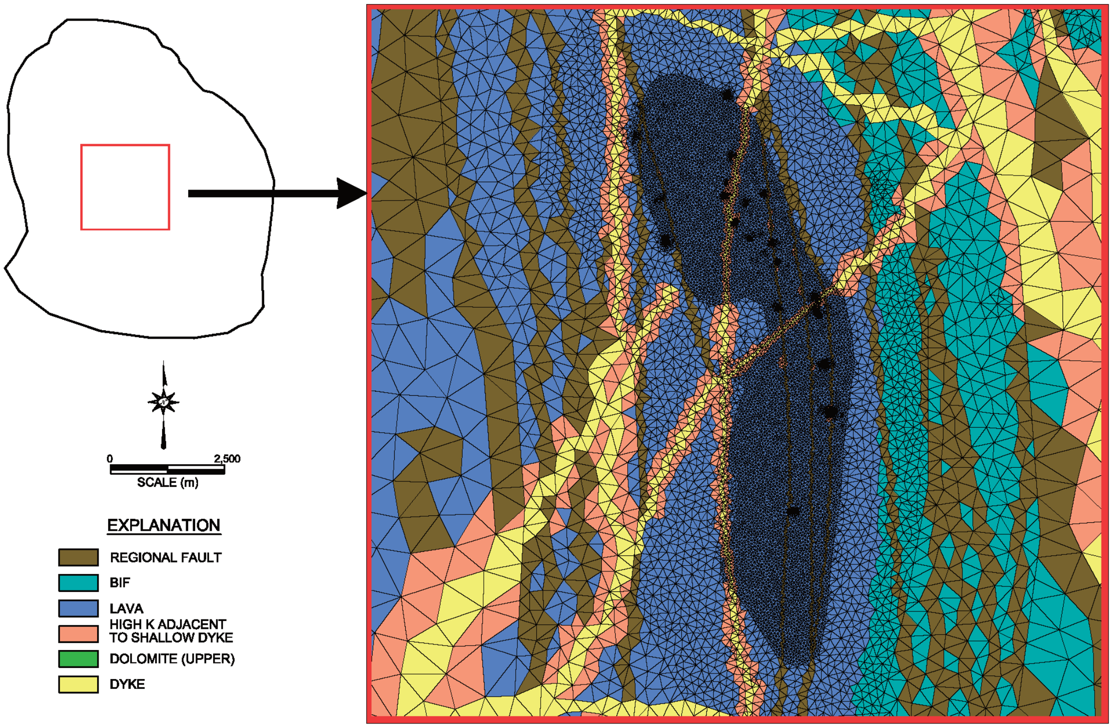

Fig. 4 *Plan View of Model Grid and Geologic Units of Model Layer 3 in Mine Vicinity*

Model Calibration

The groundwater flow model was calibrated to both pre-mining and transient conditions. Prior to simulating the mining activities, a simulation of "pre-mining, steady-state" groundwater flow conditions was conducted to establish initial groundwater conditions. Because there are limited measured water levels prior to mining at Sishen mine, the goal of the steady-state simulation was to obtain reasonable regional groundwater levels and flow directions. The model-simulated groundwater flow direction is from the southeast to the northwest, as observed at the site.

Using the water levels derived from the "pre-mining, steady-state" simulation, a transient model calibration was conducted by simulating the dewatering wells and pit excavation from January 1953 to December 2010. The measured water levels from 60 monitoring wells and piezometers were used in the calibration.

In addition to water levels, residual passive inflow (RPI), which refers to the seepage rate to the pit under active dewatering conditions, was also used in the model calibration. No RPI occurs at the site in 2011, which is also observed in the model simulations.

Predicted Dewatering Requirements

The current phase of the investigation focuses on the prediction of dewatering requirements for future mining. The key objective in designing the dewatering system is to use the minimal number of dewatering wells to achieve 'dry' working conditions over the life of the mine (LOM). Dewatering wells were simulated with assigned initial pumping rates. A "freeboard" of 25 m (the minimum required water column above the pumps) was assigned to each existing pumping well to ensure that the water level in the pumping well was maintained 25 m above the bottom of the well. For each of the new pumping wells, the bottom elevation of the well was assumed to be at 725 mamsl; and the pumping water level was assumed to be at 750 mamsl, again maintaining 25 m of "freeboard". During the dewatering simulations, if and when the simulated water level in a dewatering well reached the "freeboard" elevation, the dewatering well was then simulated as a drain boundary condition.

In order to simulate the optimum dewatering rates required for maintaining 'dry' working conditions, 16 "modeled monitoring points" were selected at various pits to compare the simulated water levels to future bench elevations. The results from the model simulations suggest that the current dewatering capacity is not sufficient to maintain 'dry' working conditions for LOM; therefore an additional 11 dewatering wells with an initial pumping capacity of 100 m^3/hr are required for LOM. The maximum dewatering rate is predicted to increase from the current value of 1,500 m^3/hr to approximately 2,600 m^3/hr.

Future Investigations

The current model focuses on dewatering requirements. Although the model is still in the preliminary stage, it has provided valuable guidance for future project planning. Updates of the model will focus on:

- refining the localities and characteristics of structures (faults and dykes);
- assessing the relative contribution from the Chert unit and regional structures to dewatering;
- evaluating the impacts of enhanced recharge through swallets on dewatering requirements;
- developing and incorporating information of the *K* of the lower hydrogeologic units (especially the Chert zone), the faults, and the bands of high permeability along the dykes; and
- evaluating the cumulative impacts of dewatering from Sishen and other mines on the water demands of stakeholders.

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