Delineation of Zones at Risk from Groundwater Inflows at an Underground Platinum Mine in South Africa

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ABSTRACT: The subject mine has a policy of avoiding groundwater inflow into the underground workings due to the impact on the mine operations. It has already implemented a significant mitigation measure by excluding shallow mining and a large sacrificial pillar under the river that is present in the mining area. To assess the risk of groundwater inflow into the underground mine workings for a planned mine expansion project, ERM undertook numerical groundwater modelling using FEFLOW. The groundwater flow models, based on a detailed geological investigation, were used to define the proposed mining area into high, medium and low risk areas with respect to potential groundwater inflow. The conceptual definitions of the Mining Risk Areas are (i) High Risk – general groundwater seepage and inflow expected in the face and roof of the mining unit from numerous joints and fractures which is regarded as serious enough to permanently halt mining operations; (ii) Medium Risk – possibility of limited point source groundwater inflow in the face and roof of the mining unit from sporadic selective joints and fractures. Not expected to halt mining operations; and (iii) Low Risk – no significant groundwater risk to mining operations expected. The areas identified as being potentially at risk from groundwater inflow were determined using a combination of geological mapping, ground geophysics and percussion drilling that was incorporated into a numerical groundwater flow model. The study undertaken by ERM enabled the mine to incorporate the identified mining risk zones into the early stages of the mine planning, and allowed for a significant reduction in the size of the safety pillar under the river.

INTRODUCTION

Anglo Platinum Ltd. had been mining for platinum group elements (PGE's) at the subject mine in the Northwest Province of South Africa for a number of years. In 2009 mining operations had to permanently be halted due to significant groundwater ingress into the underground workings. Historically water ingress was mitigated by maintaining a safe mining distance from a perennial river and by ensuring that mining only took place from a depth of 30 metres below ground level (mbgl) along the north-east dipping UG2 reef. As platinum mining in this area is typically a fairly dry mining operation, mines are not equipped to deal with the water ingress volumes as experienced in 2009.

ERM investigated potential groundwater concerns associated with a planned shallow mining expansion under, and to the west of, the river using the room and pillar mining method. The main objective of the study was to delineate groundwater inflow risk zones and identify the locations of safety pillars (areas to be left un-mined) to maintain underground mine stability and limit groundwater inflow into the mine workings.

SITE DESCRIPTION

Site Locality and Geology

Mining currently takes place along the northern side of the river valley. The valley side slopes gently southwards from the local watershed to the active channel of the river. The west to east flowing river changes its flow direction to northerly upstream of the proposed mining area which is traversed by the now northerly flowing river.

The project area overlies rocks of the Upper Critical Zone of the Rustenburg Layered Suite which dip at ten degrees north-east. The lowest unit consists of the UG2 pyroxenite which sub-outcrops along the river valley. The UG2 pyroxenite is overlain by a thick series of anorthosites, leuconorites and norites which underlie the remainder of the project area. The UG2 pyroxenite contains a series of chromitite layers, the most significant of which is UG2 which is mined for its PGM content. Table 1 provides the general geology succession in the project area and Figure 1 presents a typical geological cross-section.

Geological Succession - Lithology	Geological Unit		Average Width (m)
Norite and Leuconorite	NA	NA	NA
Mottled & spotted anorthosite	Hanging wall Anorthosite		>10
Feldspathic pyroxenite	UG2 Pyroxenite	NA	4.930
Chromitite layers (UG2T3, UG2T2, UG2T1) pyroxenite		Triplets (UG2T)	1.304
Feldspathic pyroxenite (inc. 2 chromitite partings)		NA	4.746
Chromitite layer (UG2L - UG2 Leader)		Mining Unit (1.888 m)	0.201
Feldspathic pyroxenite (inc. chromitite partings)			0.997
Chromitite layer (UG2)			0.690
Footwall pegmatoidal feldspathic pyroxenite		NA	0.630
Norite (Footwall Norite)	Footwall Norite		>3

Table 1: General Geology Succession

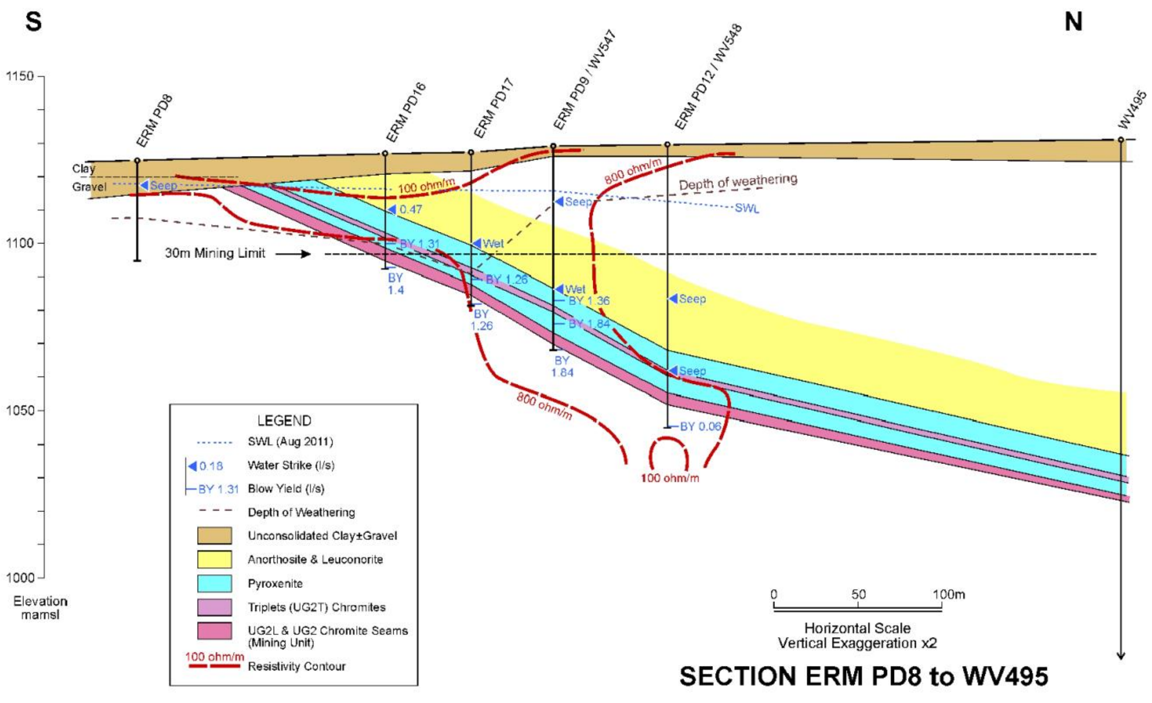

Figure 1: Typical Geological Cross-Section

The northern part of the project area is underlain by intrusive ultramafic and mafic rocks of the northerly dipping Rustenburg Layered Suite which form an undulating plain overlain by a thin black turf soil cover. The rocks of the Rustenburg Layered Suite overlie older floor rocks to the south composed of generally north dipping quartzites, shales and hornfels of the Transvaal Supergroup (Pretoria Group) that outcrop to the south as a positive relief feature.

HYDROGEOLOGICAL CONCEPTUAL MODEL

Three main hydrostratigraphic units (HU) were identified in the project area (i) Alluvial HU, (ii) Shallow Weathered Bedrock HU and (iii) UG2 Pyroxenite HU. Increased bedrock permeability associated with deep zones of weathering and open joint sets allow hydraulic connection between the units, which was confirmed by pumping tests. The conceptual model is presented in Figure 2.

Alluvial Hydrostratigraphic Unit

The Alluvial HU on the banks of the river is composed of unconsolidated gravel and silt deposits with an average thickness of 5 m and overlies weathered bedrock. Blow yields (the volume of water per unit of time blown from the borehole during drilling) encountered in this unit are mostly only seepage and below 0.5 L/s with exception of one borehole, which had a blow yield of 5.2 L/s. This particular borehole is located within an abandoned palaeo channel related to lateral migration of the active river channel, which is 16 m deep in this particular location. Hydraulic conductivities (K) in this unit vary from 0.06 to 2 metres per day (m/d) and transmissivity (T) of 0.2 to 2 square metres per day (m^2/d). Static water level recorded in the alluvial boreholes are approximately at the same level as the water strikes, indicating unconfined groundwater flow conditions.

Shallow Weathered Bedrock Hydrostratigraphic Unit

The Shallow Weathered Bedrock HU generally underlies the Alluvial HU where present and suboutcrops in other areas. It is composed of highly weathered and fractured (jointed) mafic and ultramafic rocks (norite, anorthosite and pyroxenite) of the Bushveld Igneous Complex. Boreholes drilled in this aquifer indicate blow-out yields slightly higher than in the Alluvial HU, however 85% of the blow yields were below 1 L/s. The Shallow Weathered Bedrock HU can broadly be divided into two major rock types, norites and pyroxenites. Different weathering in the two rock types result in different hydrogeological characteristics. Pyroxenites weather much more readily than norites resulting in higher hydraulic conductivities. K values for the weathered pyroxenites range from 0.4 to 4 m/d (T from 4 to 100 m^2/d). Rapid change in hydraulic properties observed across a relatively short distance is an indication of the aquifer heterogeneity associated with fracture (joint) density changing over a short distance. The position of the rest water levels is mostly higher than the water strike position, which indicates confined groundwater flow conditions. However, since an uninterrupted confining layer is absent, it has been classified as a semi-confined unit.

UG2 Pyroxenite Hydrostratigraphic Unit

The UG2 Pyroxenite HU lies below the Shallow Weathered Bedrock HU and is confined to the triplets, anorthosites and adjacent parts of the UG2 pyroxenite at shallow depth. The unit thins out along the dipping UG2 reef and is confined to the triplets only at greater depths. No evidence of water occurrences was established in the triplets deeper than 70 mbgl. Blow yields are generally higher than in the overlying units and decrease with depth due to the compaction of the opening width of fractures in the triplet zone. K values range from 0.02 to 9 m/d (T from 0.6 to 50 m^2/d).

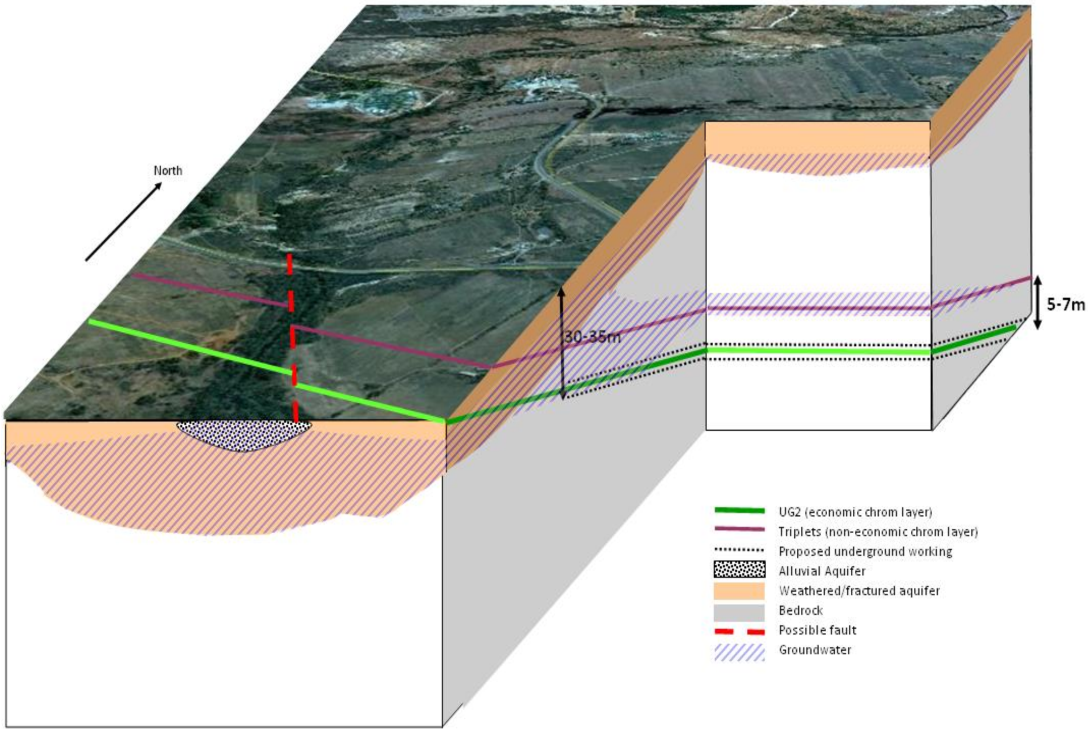

Figure 2: Hydrogeological Conceptual Model

GEOLOGICAL MINING RISK ASSESSMENT

Results from the geological, geophysical and hydrogeological studies were used as a basis for a risk assessment to provide input for the numerical groundwater modelling. The planned mining areas were classified as high, medium and low mining risk areas with respect to potential groundwater inflow. The conceptual definitions of the mining risk areas are:

- **High Risk** – general groundwater seepage and inflow expected in the face and roof from numerous joints and fractures within the UG2L / UG2 mining unit similar to that encountered in 2009/10 which was regarded (along with poor ground conditions) as serious enough to permanently halt mining operations;
- **Medium Risk** – possibility of limited point source groundwater inflow in the face and roof of the UG2L / UG2 mining unit from sporadic selective joints and fractures. Not expected to halt mining operations; and
- **Low Risk** – no significant groundwater risk to mining operations expected.

Preliminary mining risk areas (in order of significance) were identified based on the findings of (i) percussion drilling blow yields, (ii) core drilling (weathering) and (iii) geophysical survey (resistivity). The specific criteria are detailed below:

- In terms of blow yields recorded during the percussion drilling campaign, blow yields measured at the elevation of 2 m below the UG2T (triplets) returning >3.99 L/s were classified as high risk areas and blow yields measured returning 1 - 3.99 L/s as medium risk;
- High risk areas, based on geological data, are where the bedrock weathering zone developed between surface and the base of the surface weathering profile impacts upon the elevation of the UG2L / UG2 mining unit; and
- High Risk Areas based on geophysical resistivity data where low resistivity (high conductivity) zones <200 ohm/m impact upon the elevation of the UG2L / UG2 mining unit. Medium Risk Areas based on geophysical resistivity data where low to moderate resistivity (moderate to high conductivity) zones 200 - 400 ohm/m impact upon the elevation of the UG2L / UG2 mining unit. Low Risk Areas based on geophysical resistivity data where moderate resistivity (moderate conductivity) zones 400 - 800 ohm/m impact upon the elevation of the UG2L / UG2 mining unit.

The final determination of the extent of the high, medium and low risk areas were defined using numerical groundwater models based on steady state simulations of inflows into the mine workings.

NUMERICAL GROUNDWATER MODELLING

Model Setup

The model domain includes the subject mine area and extends over an area of approximately 51 km^2 (Figure 3). The model boundaries were chosen according to identified hydrogeological and hydrological boundaries and included a constant head boundary condition (1st order) along the river in the north-east and no flow boundary condition (2nd order) along the rest of the model boundary simulating watersheds.

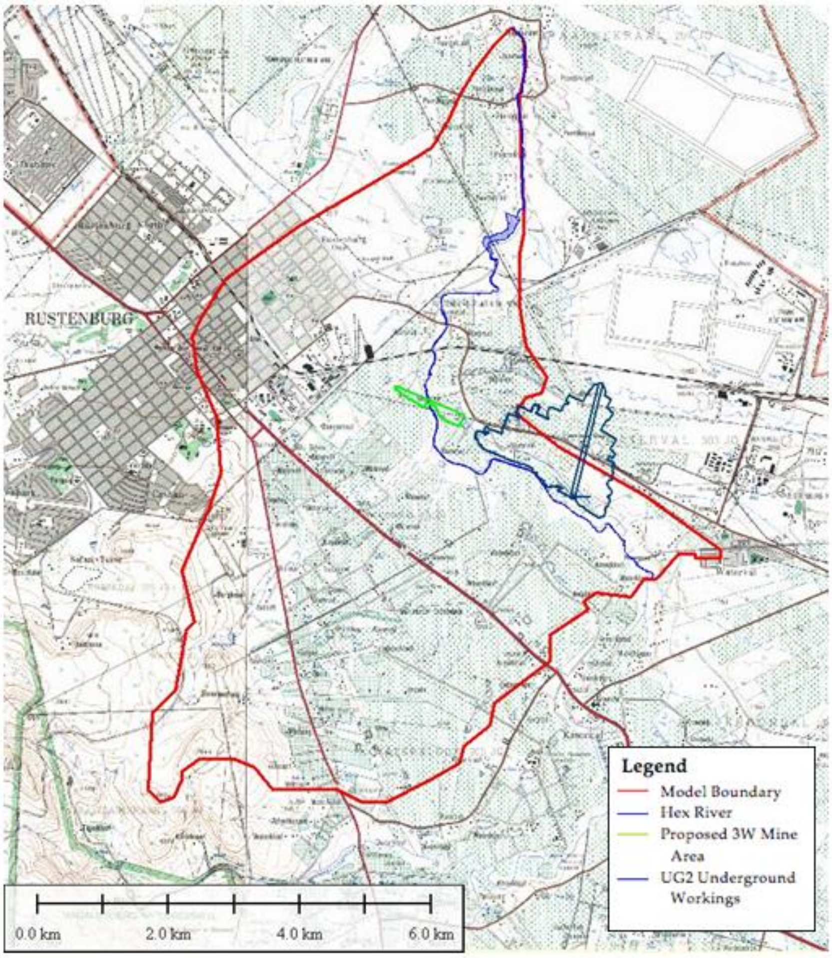

Figure 3: Model Domain

To achieve the model objectives, the complex geology / hydrogeology was represented using six model layers as follows (Figure 4):

- Layer 1: Alluvial HU (static water levels to bottom of alluvium, where present);
- Layer 2: Shallow Weathered Bedrock HU (static water levels where alluvium not present, otherwise alluvium bottom to bottom of weathering);
- Layer 3: Aquitard One between Shallow Weathered Bedrock HU and UG2T & AN HU (only present north of UG2 reef);
- Layer 4: UG2T & AN HU;
- Layer 5: Aquitard Two between UG2T & AN HU and UG2; and
- Layer 6: UG2 (mining layer).

The base of the model was defined as the base of the Shallow Weathered Bedrock HU south of the UG2 reef sub-outcrop and at the bottom of the UG2 (mining layer) north of the UG2 reef sub-outcrop. Where the UG2 (mining layer) was deeper than 70mbgl, a constant depth (flat base) was assumed.

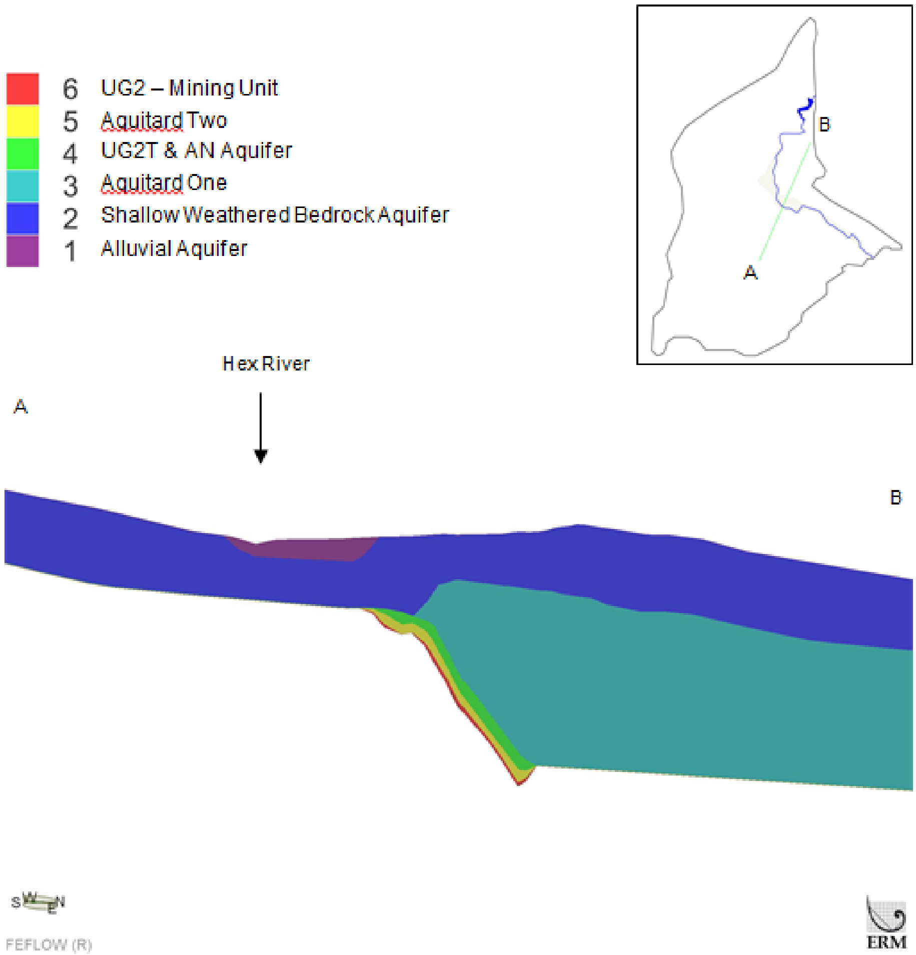

Figure 4: Model Geometry

Hydraulic Conductivities

Horizontal hydraulic conductivities (K_h) were specified per hydrostratigraphic unit based on the pumping test results. In the absence of site specific field data for vertical conductivities (K_v) these were generally set at one tenth of K_h. K_v in Layers 4 to 6 (dipping UG2 reef) were increased for different risk areas defined, based on the results of the geological mining risk assessment. For the medium risk area K_v was increased by a factor 10 and for the high risk by a factor 100 to account for the different degree of open joints and fractures between the UG2T & AN HU and the UG2 mining layer.

K values for the UG2T to AN and UG2 units were decreased with depth due to the compaction of the opening width of fractures in the triplet zone (based on pumping test results). Table 2 provides a summary of K implemented in layers 1 to 3 and Table 3 details K values for layers 4 to 6.

Unit	Horizontal Hydraulic Conductivity	Vertical Hydraulic Conductivity
Alluvium	3.E-01	3.E-02
Weathered Pyroxenite	5.E-01	5.E-02
Weathered Norite	5.E-02	5.E-03
Aquitard One	1.E-04	1.E-05

Table 2: Model Hydraulic Conductivities (Layer 1 to 3) in m/d

Unit	Horizontal Hydraulic Conductivity		Vertical Hydraulic Conductivity					
			Low Risk		Medium Risk		High Risk	
	shallow	deep	shallow	deep	shallow	deep	shallow	deep
UG2T to AN	5.E-01	4.E-02	5.E-02	4.E-03	5.E-01	4.E-02	5.E+00	4.E-01
Aquitard Two	1.E-04	NA	1.E-05	NA	1.E-04	NA	1.E-03	NA
UG2	5.E-02	4.E-03	5.E-03	4.E-04	5.E-02	4.E-03	5.E-01	4.E-02

Table 3: Model Hydraulic Conductivities (Layer 4 to 6) in m/d

Steady State Model Calibration

During the model calibration phase, recharge was optimized in order to obtain an acceptable fit of calculated versus observed water levels. A total of 78 groundwater level measurements were available in the model domain for model calibration. The calibrated value for recharge was $4*10^{-6}$ m/d, which corresponds to 0.2% of mean annual precipitation (MAP) of 660mm/a. A constant recharge value was applied over the entire model domain. Calculated piezometric heads were compared to observed heads in the scatter diagram presented in Figure 5. The normalised root mean square error of the model calibration was 8.5 %, which was considered acceptable to achieve the model objectives.

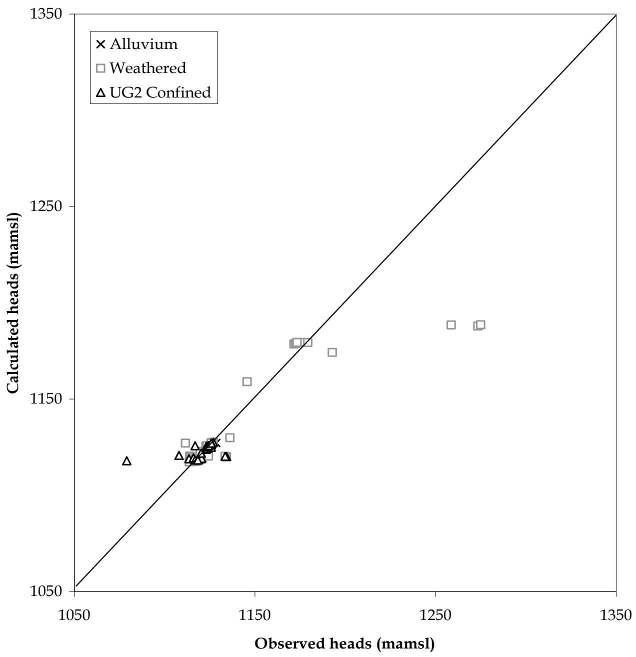

Figure 5: Scatter Diagram Model Calibration

Modelling Results

Risk Zone/Pillar Delineation

To delineate risk zones for underground mining, potential mine water ingress was modelled. Constant head cells were implemented in the UG2 – mining unit (layer 6) in the calibrated steady state model at an elevation equal to the floor of the unit. Mining was simulated from the 30 m mining limit to approximately 70 m vertical depth (bottom of the model) to cover the planned mine and the immediate surroundings. Risk classes as described in the mining risk assessment section above were calibrated against encountered mine ingress at the current and historical operations that had stopped mining operations. For example zones at the proposed mine, where similar inflow rates were simulated, were classified as high risk. The resulting risk zones are presented in Figure 6.

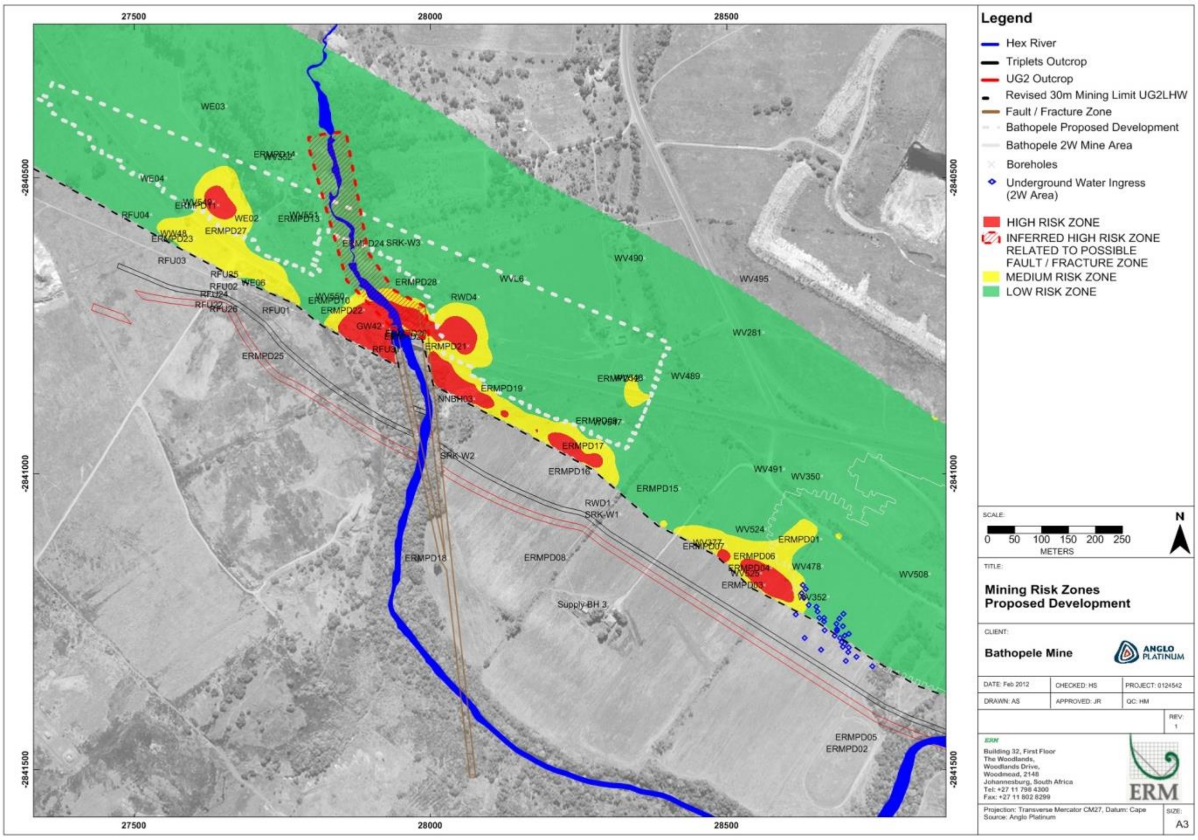

Figure 6: Mining Risk Zones

CONCLUSIONS

Zones depicting different risk profiles associated with potential groundwater ingress into the planned mine expansion were delineated using numerical groundwater modelling. Two high risk areas were identified that are surrounded by a medium risk envelope, one being east and the other west of the river. ERM recommended that high risk areas be excluded from the mine plan as groundwater inflows may lead to mining operations being terminated. The identified medium risk areas, however, can be mined, subject to suitable control and safety procedures that include cover drilling, if the specific conditions allow it. In addition, underground mining of designated high risk areas could be considered if cover drilling confirms that the geological, geotechnical and groundwater conditions are suitable. This study has enabled mine planners to incorporate the identified mining risk zones into the early stages of the mine plan and allowed for a significant reduction in the size of the safety pillar under the river.

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