Unravelling the Convoluted Marbles of a Namibian Gold Mine

W. Chimhanda[1], D.M. Duthe[1], L Kawali[2]

[1]Itasca Africa (Pty) Ltd, P. O. Box 3918, Rivonia 2128, South Africa; dduthe@itasca-africa.com, wchimhanda@itasca-africa.com
[2]B2Gold Namibia (Pty) Ltd, PO Box 80363, Olympia, Windhoek, lkawali@b2gold.com

Abstract

Otjikoto Gold Mine is located in the arid northern part of Namibia in the Okonguarrie schists and marbles of the Damara Orogeny and 70 km to the SW of Kombat underground copper mine that suffered serious flooding in 2005. The over folded synclines and anticlines have resulted in a complex hydrogeological environment that required an extensive geochemical and hydrogeological field programme to understand the zones of recharge, storage and risks in terms of groundwater ingress to the open pit mining operations.

Hydrochemical and isotope fingerprinting (stable isotopes and tritium), has shown that a source of the groundwater ingress to the mine, (located in the low permeability schists and albitites of the Okonguarrie Formation) is the Karibib Marbles, an important regional aquifer, supplying the nearby towns. North-south fault structures have provided hydraulic connection to the limbs of the Karibib anticline transecting the intermediate Ghaub diamictite and aquitard, resulting in recharge to zones with enhanced storage capacity along the fold axes and albitised contacts of the Okonguarrie Formation marble stringers. The conceptual hydrogeological model includes a complex interlayering due to allogenic and autogenic recharge of the marbles, clearly distinguishable from the hydrochemistry and piezometric responses to testing of a prototype dewatering borehole with linear flow.

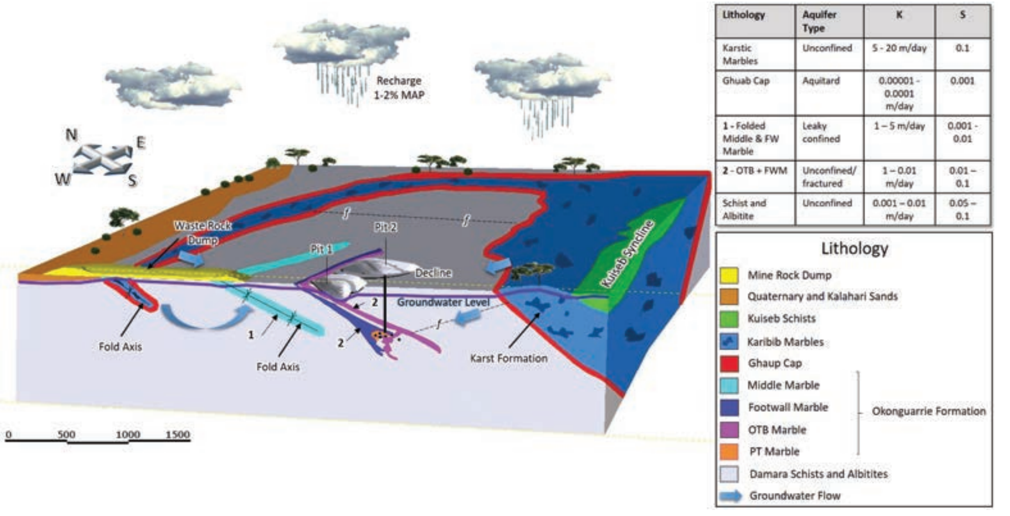
To quantify the ingress rates and evaluate pore pressures behind the heterogeneous and anisotropic pit high walls, a numerical flow model was developed to simulate the complexities of the conceptual hydrogeological model. Predictive simulations indicate groundwater ingress rates to the pit can be reduced significantly by targeting the marble structures and dewatering the confined aquifer, which also acts as an underdrain to depressurizing the overlying less permeable schists.

The combined collection of geochemical and hydrogeological data was used to unravel the sources and recharge mechanisms of ingress to the pits and to quantify the potential for acid rock drainage following closure of the mine.

Introduction

A gold mine is located in the arid northern part of Namibia in the Okonguarrie schists and marbles of the Damara Orogeny and 70 km to the SW of Kombat underground copper mine that suffered serious flooding in 2005. The over folded synclines and anticlines have resulted in a complex hydrogeological environment that required an extensive geochemical and hydrogeological field programme to understand the zones of recharge, storage and risks in terms of groundwater ingress to the open pit mining operations.

Hydrochemical and isotope fingerprinting (stable isotopes and tritium), has shown that a source of the groundwater ingress to the mine, (located in the low permeability schists and albitites of the Okonguarri Formation) is the Karibib Marbles, an important regional aquifer, supplying the nearby towns. North-south fault structures have provided hydraulic connection to the limbs of the Karibib anticline transecting the intermediate Ghaub diamictite and aquitard, resulting in recharge to zones with enhanced storage capacity along the fold axes and albitised contacts of the Okonguarrie Formation marble stringers. The conceptual hydrogeological model includes a complex interlayering due to allogenic and autogenic recharge of the marbles, clearly distinguish-



Lithology	Aquifer Type	K	S
Karstic Marbles	Unconfined	5 - 20 m/day	0.1
Ghuab Cap	Aquitard	0.00001 - 0.0001 m/day	0.001
1 - Folded Middle & FW Marble	Leaky confined	1 – 5 m/day	0.001 - 0.01
2 - OTB + FWM	Unconfined/ fractured	1 – 0.01 m/day	0.01 – 0.1
Schist and Albitite	Unconfined	0.001 – 0.01 m/day	0.05 – 0.1

Figure 1 *Conceptual hydrogeological model*

able from the hydrochemistry and piezometric responses to testing of a prototype dewatering borehole with linear flow.

Conceptual Hydrogeologic Model

Figure 1 shows the conceptual hydrogeological model of the mine area. Regional geological information, mine geological model and lithological models provided by the mine were used to develop a Leapfrog regional model, which is the basis of the conceptual and numerical groundwater model.

The outcropping Karibib Marble forms the topographical highs and has higher groundwater potential due to the recharge from rainfall via the karsts and sinkholes. This is the major aquifer that is used regionally by surrounding farmers. The Ghaub Cap at the base of the Karibib Marbles is considered an aquitard restricting groundwater flow from the Karibib Marbles resulting in the differential piezometric head between the marbles and the Okonguarri Formation.

Although the schists and albitites of the Okonguarri Formation have lower permeability, there is hydraulic connection via faults and structures to the surrounding Karibib Marbles, resulting in the localised development of water bearing zones, particularly associated with the fold hinges of the marbles of the Middle Okonguarri Formation (OTB, Middle (OTJ) Marble and FW Marble) as supported by aquifer testing results. In reality, although the marble bands are conceptualised as discrete units separated by albitite, according to the geological logs, there are several stringers and lenses of marble in the entire marble package (OTB, FWM including the intermediate albitite) which is generally 60 m in thickness, increasing in the south to > 100 m. The hydraulic connectivity between the marble bands could therefore be significant, particularly in fault zones or major joints.

There is also direct but lesser recharge of the unconfined OTB and FW marble bands through the overlying calcretes and schists, resulting in a similar water type but showing increased ion exchange, older in signature and being more depleted in deuterium (more negative del 2H) due to the longer flow path through the calcretes. The recharge for this arid area occurs following >1:5 Year events as intense precipitation and consecutive rainfall days, when rainfall exceeds evaporation. Infiltration to the groundwater table can occur through the sinkholes and cavities in the outcropping Karibib Marbles as well as, to the lesser extent, through the calcrete. An estimate of recharge to groundwater as 20% during years with higher rainfall (>700 mm/annum) results in a rise in the water table, that slowly dissipates until the next extreme rainfall period. However, for modelling purposes, this is considered the cumulative rainfall over a 10 year period (following a 1:10 year rainfall event and the remaining years recharge

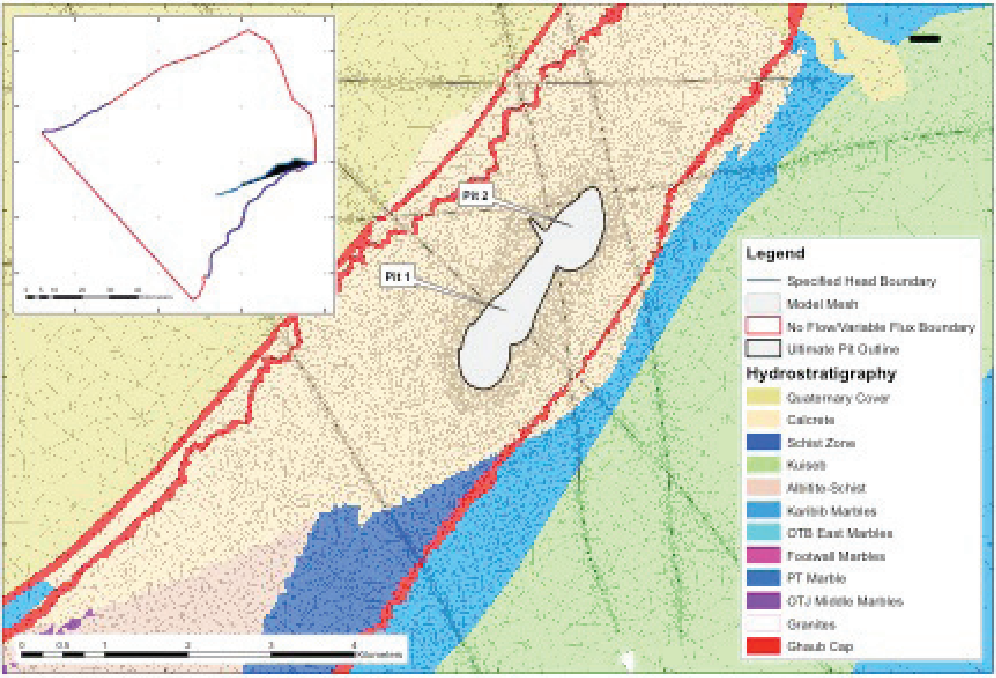


Figure 2 *Plan View Showing Discretization and Hydrostratigraphy with pits*

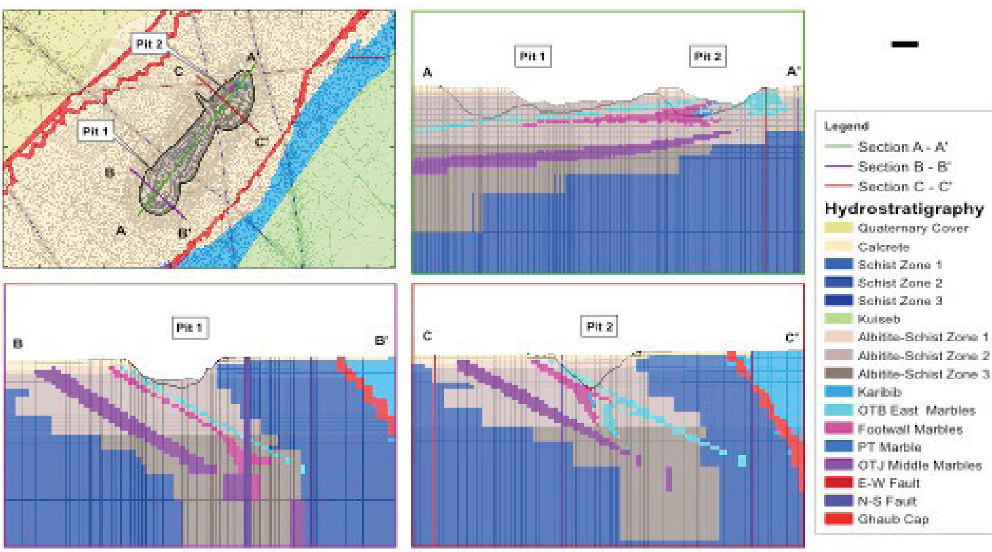


Figure 3 *Section View Showing Discretization and Hydrostratigraphy with pits*

is considered negligible) and the simulated annual recharge estimate is therefore 2 % of the MAR in the Karibib Marbles (with karstic landform) and less for the diffuse allogenic recharge lower permeability Okonguarrie Formations overlain by calcrete (<1%).

Numerical Groundwater Model

The 3-D numerical groundwater flow model was constructed based on the conceptual hydrogeological model using the finite element code MINEDW version 3.04 (Azrag et al., 1998). The numerical groundwater model domain is shown in Figure 2 as well as the model boundaries.

For the steady-state simulation, the south-eastern and part of the north-western model boundary were assigned as specified heads with the hydraulic head set equal to the topographical elevation and coincide with the main rivers that drain into the Ugab Catchment to the west and the Upper Omatoko Basin to the north-east. The model domain is quite large in order to include the Karibib Marbles which is the main water supply aquifer in the region. Therefore in the absence of any other significant hydrological features the remaining boundaries were set at an arbitrary distance of approximately 30 km from the mine. These were assigned as no flow boundaries during steady state. For the transient simulations, the no flow boundaries were changed to variable-flux boundary conditions.

The bottom boundary of the model is defined as a no-flow boundary at the somewhat arbitrary elevation of 300 mamsl, about 1000 m below base of the Pit 1 and Pit 2 (1260 and 1355 mamsl respectively) so that the boundary would have no influence on the predictive simulations of the model. The upper model boundary of the groundwater flow system is the phreatic surface, which is calculated by the model.

Model Grid and Discretization

The model mesh is finely discretised in the mine footprint area comprising of the pits to enable better numerical resolution and to represent the hydrostratigraphic units in detail as shown in Figure 3. The horizontal dimensions of the elements in mine footprint area are approximately 20 to 30 m. The model mesh was vertically discretised into approximately 15 m thick layers over the vertical pit extent to adequately represents the significant hydrostratigraphic units while still maintaining numerical efficiency and to enable a refined determination of the seepage faces.

In the mesh, the primary hydraulic properties (i.e., the hydraulic conductivity, specific storage, and specific yield) are assigned to the elements representing the various hydrostratigraphic units, and the model-calculated heads and flows are associated with the nodes. During simulation of mining, the finite-element grid within the pit is "collapsed" to represent the changing configuration of the pit. The hydraulic properties of the collapsed elements are changed as necessary to maintain the original "hydrostratigraphy" of the pit area.

Simulation of Open Pits

Using a model time step of one month, the elevation of the pit bottom was assumed to change every month during the period of simulation, the 10-year Life of Mine (LoM) up to December 2023. The monthly configuration of the pit was linearly interpolated between the original ground surface and the planned yearly pit configuration.

Using this methodology, excavation of the pit with time was simulated in the model with nodes within the pit being assigned time-variable elevations using the collapsing grid capability of *MINEDW*. A node representing the pit sides or bottom, a special type of drain node, produces water if the model-calculated groundwater level at the node is higher than the specified elevation of the node. If the calculated groundwater level is lower, the drain node is simply dry. *MINEDW* thereby enables a very realistic simulation of the pit configuration and inflow conditions. In each time step of the numerical simulation, the elevations of all of the drain nodes are specified and changed as necessary to replicate the mine plan.

The stress releases to the rock and disturbance to the rock due to excavation results in the rock beneath the pit benches to be more permeable than the in-situ rock. The disturbed rock is referred to as the zone of relaxation (ZOR). The thickness of the ZOR could be as thick as several hundred meters. *MINEDW* is able to simulate the development of the ZOR according to the mining schedule by increasing the K value of the ZOR along the depth as time-variant conductivity. Simulations of the development of the ZOR according to the mining schedule are important in the prediction of pore-pressure distribution within the slope. The ZOR was simulated for the pits as 1/3 of the pit depth as time-variant conductivity.

Simulation of Hydrogeology

The hydraulic parameters of importance in investigating groundwater flow are hydrau-

Table 1. Summary of the Scenarios for Predictive Simulation

Scenario	Description
1	Predictive simulations with pits and current water supply holes
2	Predictive simulations with pits, current water supply holes with dewatering from the following holes: PB1(200m^3/hr); PB2(80m^3/hr); PB3(70m^3/hr); PB4(2m^3/hr); and PB5(80 m^3/hr).

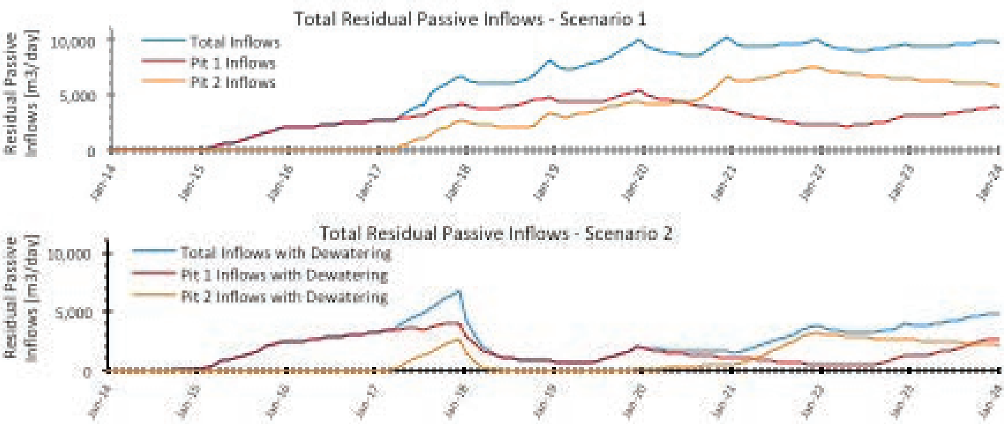


***Figure 4** Predicted Residual Passive Inflows Scenario 1 and 2*

lic conductivity, specific storage and specific yield. These parameters control the ease with which groundwater can move through the subsurface and how much water can be released from the system, thus are important to estimate inflows into the pits, propagation of drawdown and ability to depressurise. The primary hydraulic parameters are assigned to the elements representing the various hydrostratigraphic units, and the model-calculated water levels and flows are associated with the nodes. The simulated hydraulic properties of the various units in the model, after steady state and transient calibration, are within the range of the values determined from the packer testing and test pumping and included in the conceptual model (Figure 1).

Predictive Simulations

The predictive simulations were conducted to quantify the ingress rates and evaluate pore pressures behind the heterogeneous and anisotropic pit high walls, as well as simulate the complexities represented in the conceptual hydrogeological model. Predictive simulations indicate groundwater ingress rates to the pits can be reduced significantly by targeting the marble structures and dewatering the confined aquifer, which also acts as an underdrain to depressurizing the overlying less permeable schists. Therefore the primary target zones for dewatering are the folded marble which are the largest contributor of groundwater to the pits.

For the purpose of the simulations, the proposed dewatering boreholes were planned to start pumping in 2018. The scenarios simulated are summarised in Table 1 where the first scenario represents the status quo at the mine and scenario 2 incorporates the proposed dewatering with the average pumping rates determined from pump testing data analysis.

Predicted Residual Passive Inflows

The predicted residual passive inflows (RPI) into the pits are shown in Figure 4 for Scenarios 1 and 2.

The predictive simulations for Scenario 1 shows that RPI into Pit 1 is predicted to increase steadily to a maximum of ≈5 530 m^3/day in December 2019. Thereafter the inflows are expected to reduce to ≈2 000 m^3/day as Pit 2 deepens and then increase steadily to ≈3 900 m^3/day at the end of the 10year LOM. Proposed dewatering, Scenario 2, will re-

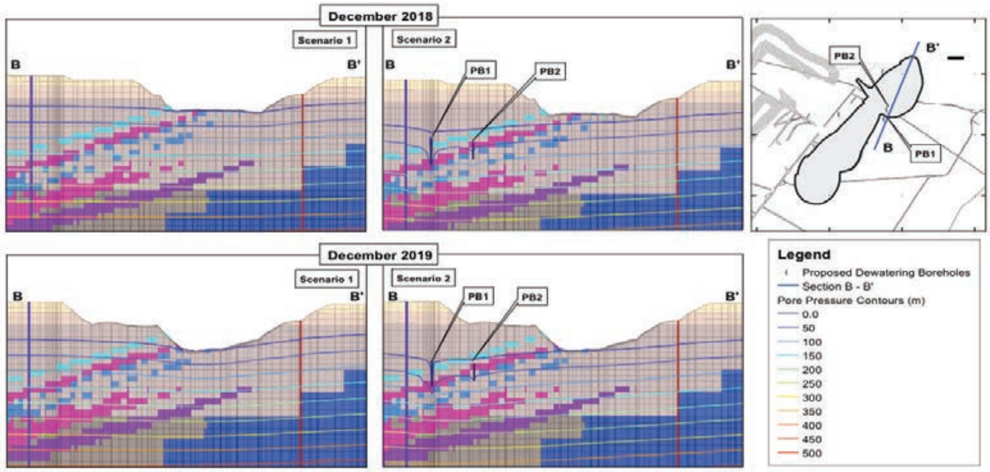


Figure 5 Section through Pit 2, PB1 and PB2 Showing Phreatic Surface and Pore Pressure – 2018 and 2019

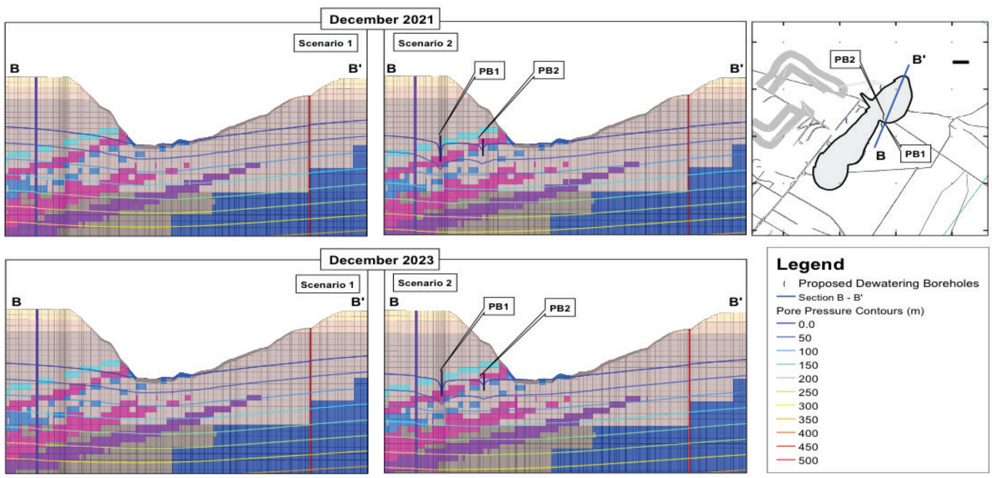


Figure 6 Section through Pit 2, PB1 and PB2 Showing Phreatic Surface and Pore Pressure – 2021 and 2023

sult in a decrease in RPI to a maximum of ≈4 000 m^3/day as the boreholes come on line. Thereafter the inflows are expected to reduce to ≈200 m^3/day as Pit 2 deepens and then increase steadily to ≈2 000 m^3/day at the end of the 10year LOM as the dewatering boreholes become less effective to dewater the deeper portions of the pit.

The predictive simulations for Scenario 1 shows that RPI into Pit 2 is predicted to increase steadily to a maximum of ≈7 600 m^3/day as the pit expand and deepens. Thereafter the inflows are expected to steadily decrease to ≈5 800 m^3/day as operations ceases in Pit 2 until the end of the 10-year LOM. Proposed dewatering, Scenario 2, will result in a decrease in RPI to a maximum of ≈2 600 m^3/day as the boreholes come on line. Thereafter there will be no inflows until 2021 where inflows are expected to increase steadily to ≈2 500 m^3/day at the end of the 10year LOM as the dewatering boreholes become less effective to dewater the deeper portions of the pit.

Phreatic Surface and Pore pressure

The phreatic surface and distribution of pore pressures for Scenario 1 and 2 are shown in Figure 5 and 6 for a section across Pit2, the PB1 and PB2 for December 2018, 2019, 2021 and 2023. The results of the simulations show that active dewatering (Scenario 2) will result in significantly lowering of the phreatic surface using proposed dewatering boreholes. The proposed boreholes are able to reduce the residual passive inflows into the pit and depressurize the pit walls. The phreatic surface will be drawn down fully in the deepest section of the pit or to below pit bottom for both pits during operation therefore there is no indication there will be build-up of pore pressures. The reduction of pore pressures is attributed to the continued depressurisation from the targeted marbles. However, localised and transient pore pressure build up could occur in response to recharge events.

Conclusions

The proposed dewatering strategy of targeting the marble structures and dewatering the confined aquifer, which also acts as an underdrain to depressurizing the overlying less permeable schists will result in a decrease of inflows into the pits. However as the dewatering boreholes become less effective to dewater the deeper portions of the pit residual passive inflows into the pits. The results of the simulations show that active dewatering will result in significantly lowering of the phreatic surface using proposed dewatering boreholes as well as depressurize the pit walls indicating that there will be no build-up of pore pressures. However, localised and transient pore pressure build up could occur in response to extreme recharge events.

A phased approach will be required to meet the operational dewatering target as the dewatering plan is optimized through predictive simulations and model update. The numerical modeling results through calibration, suggest that the spatial variation of hydraulic parameters, anisotropy and geological complexity still requires further refinement as the project advances.

The predictive simulations are therefore considered a first order approximation based on the data available and assumptions made. Improvements to the model predictions can be realized by updating the model as the understanding of the spatial variation of hydraulic parameters and\or geological complexity is acquired as the project advances.

Acknowledgements

The authors thank the Mine for allowing us to use the data from their operation for this publication for ICARD | IMWA | MWD 2018.

References

Azrag, E.A., Ugorets, V.I., and Atkinson, L.C., Use of a finite element code to model complex mine water problems: Proceedings of symposium on mine water and environmental impacts, vol. 1, International Mine Water Association (Johannesburg, September 1998)

Beale G; J Read. 2013. Guidelines for Evaluating Water in Pit Slope Stability. CSIRO, pp 600

Beyer M, M Gaj, P Koeniger, J Hamutoko, S Uugulu, H Wanke, C Lohe, T Himmelsbach and M Billib (20014) Deuterium labelling of soil water movement in the Cuvelai-Etosha Basin, Namibia Geophysical Research Abstracts Vol. 16, EGU2014-4012-2, 2014

Külls C. (2000) Groundwater of the North-Western Kalahari, Namibia – Estimation of Recharge and Quantification of the Flow Systems. Doctorate Thesis submitted at the Julius-Maximilian University of Würzburg.

Read J and P Stacey (2009) Guidelines for Open Pit Design, CSIRO Publishing pp 495