

# Implementation of a Finite Element Model to generate synthetic data for open pit's dewatering

Sage NGOIE<sup>1</sup>, Adalbert Mbuyu<sup>2</sup>, Jean Felix Kabulo<sup>3</sup>, Albert Kalau<sup>4</sup>

<sup>1</sup>Philosophiae Doctor, IGS, University of the Free State, Republic of South Africa

<sup>2</sup>Junior Lecturer, Dept. of Geology, University of Kolwezi, Dem. Rep. of Congo

<sup>3</sup>Junior Lecturer, Dept. of Geology, University of Likasi, Dem. Rep. of Congo

<sup>4</sup>Lecturer, Dept. of geology and mining engineering, ISTA Kzi, Dem. Rep. of Congo

\*\*\*

**Abstract** - Synthetic data have long been employed in geohydrology for model development and testing. The objective of this chapter is to generate a synthetic data set of geohydrological responses in an open pit environment. This data set will be used to represent real data that could be recorded at an open pit mine.

The synthetic data set is generated by using a numerical model. In the model, different pumping scenarios are considered. The model uses nine observation points (piezometers) and three, six, nine and 12 pumping wells in the four different pumping scenarios. The purpose of the pumping wells is to dewater the open pit under different pumping conditions. The response of the aquifer to these different pumping scenarios is examined.

**Key Words:** Finite Elements Methods; Synthetic data; Dewatering; Open pit mine.

## 1. INTRODUCTION

Synthetic data have long been employed in geohydrology for model development and testing. The objective of this paper is to generate a synthetic data set of hydrogeological responses in an open pit environment. This data set can be used to represent real data that could be recorded at an open pit mine.

The synthetic data set is generated by using a numerical model. In the model, different pumping scenarios are considered. The model uses nine observation points (piezometers) and three, six, nine and 12 pumping wells in the four different pumping scenarios. The purpose of the pumping wells is to dewater the open pit under different pumping conditions. The response of the aquifer to these different pumping scenarios is examined.

## 2. MODEL DESCRIPTION

Aquifers are complex and not often directly visible. For better understanding these aquifers for modelling purposes, they have to be represented by simplified versions in the form of conceptual models. The conceptual model may influence the choice of numerical method used for simulating the behaviour of the aquifers. For example, a conceptual model with complex aquifer boundaries may have to be modelled using FEM instead of FDM, since the rectangular

cells used in FDM do not allow for adequate refinement of the modelling grid.

If the conceptual model gives an accurate representation of the real aquifer, the numerical model will also be more accurate (Anderson and Woessner, 1992).

The conceptual model of the current investigation includes information on the pit geometry, geomorphology, rainfall, surface water bodies, and aquifer units as derived from the geological layers.

### 2.1 Geometry of the modelled open pit mine

The modelled open pit mine is assumed to be excavated in a sedimentary deposit with the top and bottom elevations at 1 250 mamsl and 1 166 mamsl, respectively. The plan view of the pit can be compared to a smooth closed curve, which is symmetric about its centre with the transverse, and conjugate diameters of 880 m and 370 m, respectively (refer to Fig-1).

The mine is exclusively excavated in the first geological layer (dolomite), which is 160 m thick. The pit is assumed to be excavated in an unconfined aquifer, since it is assumed that water in the voids and fractures of the dolomite is in contact with the atmosphere and is therefore under atmospheric pressure.

The vertical distance between the highest point on the perimeter of the pit and the pit floor is 84 m. The pit has nine benches with an average bench height of 9.3 m (see fig-2).

### 2.2 Topography and hydrography of the modelled area

The general topography of the region is gentle. The pre-mining topography shown in fig-3 is an existing topography of a tropical area in the Democratic Republic of Congo (DRC). This particular area was chosen because of the variation in the surface topography (higher elevations in the southwestern parts and lower elevations in the northeastern parts). Since groundwater elevations generally emulate the surface topography, topographic gradients are often also associated with hydraulic gradients and thus with groundwater movement (Haitjema and Mitchell-Bruker, 2005). In this research, it is, therefore, assumed that the

groundwater flows in the direction of the topographic gradient.

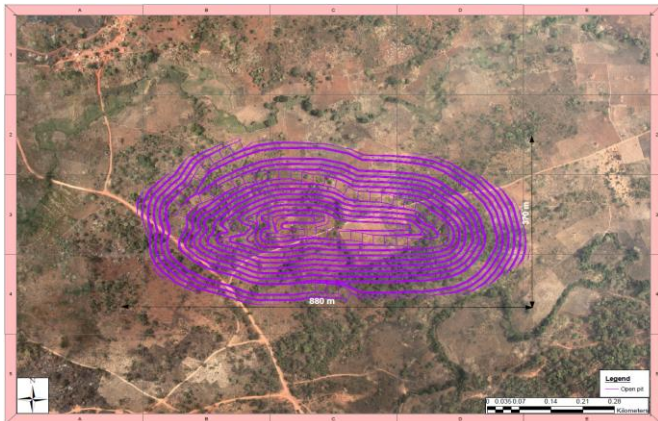


Fig - 1: Plan view of the open pit of the model

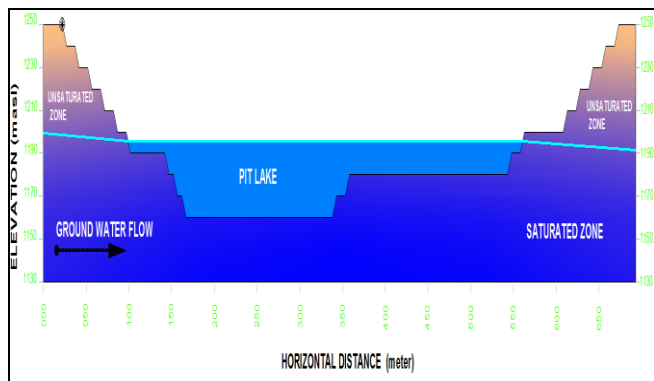


Fig - 2: Cross-section through the open pit of the model

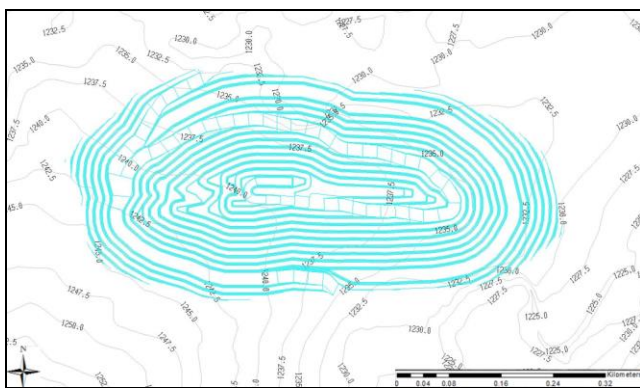


Fig - 3: Pre-mining topography of the model

The open pit is located on the watershed between two catchments, each catchment drained by a river flowing from south-west to north-east. These two rivers are simulated as constrained head boundaries. The constrained heads were assigned values that ensure a gradient in the direction of the river flow (down-gradient, according to the ground topography). It was further assumed that the water from the river infiltrates the aquifer at a constant rate of 30 m<sup>3</sup>/h. This latter infiltration rate was chosen because it was observed by Norris (1983) in the Scioto River in south-central Ohio (from 0.06 to 0.19 million gallons per day for

one acre) and also in the Dipeta River in the Democratic Republic of Congo (30 m<sup>3</sup>/h for a river with a length of 1.3 km and a width of 3 m).

Based on the topography of the model, some of the surface runoff drains directly into the open pits. Such runoff water could pose problems to the management of surface water at real mines. However, in this paper, surface runoff water entering the pit will not be considered in the synthetic model, since the aim is to model pit dewatering by using abstraction wells.

2.3 Geometry of the groundwater model

The model domain is 1 126 m long, 574 m wide and 240 m high. As shown in fig-4, the geology of the region is assumed to be sub-horizontal, consisting of only two layers, namely: a dolomite layer (160 m thick), overlying a shale layer (80 m thick). No prominent tectonic features, such as faults, occur within the model domain. The open pit mine is excavated exclusively in the dolomite layer to depth of 84 m.

2.4 Hydraulic parameters

In fig-4, the spatial distribution of the hydraulic parameters is shown. It is seen that these parameters are directly related to the geological units, and that these parameters do not vary within the geological units. As indicated in Table-1, the hydraulic conductivity is the only hydraulic parameter that differs for the two layers in the model. It is also seen that the vertical hydraulic conductivities ( $K_{ZZ}$ ) of the layers are significantly smaller than the horizontal hydraulic conductivities ( $K_{XX}$  and  $K_{YY}$ ). These hydraulic conductivity values are based on the work of Morris and Johnson (1967) who conducted studies on the hydraulic parameters of several rock types. The specific storages, and the specific yields of the two layers are taken as the default values for dolomites and shales, as defined in the software.

Table 1: Hydraulic parameters of the synthetic model

Lithology	$K_{XX}$ (m/s)	$K_{YY}$ (m/s)	$K_{ZZ}$ (m/s)	Specific yield	Specific storage	Thickness (m)
Dolomite	$10^{-7}$	$10^{-7}$	$5.10^{-8}$	0.2	$10^{-4}$	160
Shale	$10^{-12}$	$10^{-12}$	$10^{-13}$	0.2	$10^{-4}$	80

2.5 Recharge

The main recharge of the aquifer is through rainfall. The mean annual rainfall (MAR) in the modelled area is assumed to be 1 200 mm, corresponding to the rainfall figures in a tropical climate. A large percentage of the rainfall flows to rivers as runoff. In Feflow, rainfall is modelled as aerial groundwater recharge by using sink/source formulations. Recharge values for carbonate rocks such as limestone and dolomite range from three to 10% (MWR, 2009). This boundary condition was applied to the top of the first geological layer of the numerical model. Recharge calculation

is then performed automatically according to the hydrogeological parameters (permeability, storativity, etc.) of the layers in the model.

### 2.6 Dewatering and observation wells

While performing the dewatering simulations, the behavior of the aquifer will be observed at nine observation points (OBS\_1 to OBS\_9) spatially distributed as shown in fig-5. Monitoring point OBS\_9 is used to evaluate the water elevation according the bottom of the pit because it is located right in the middle of the pit. Four dewatering scenarios will be run with three, six, nine and twelve dewatering wells. The dewatering wells are numbered BH\_1 to BH\_12.

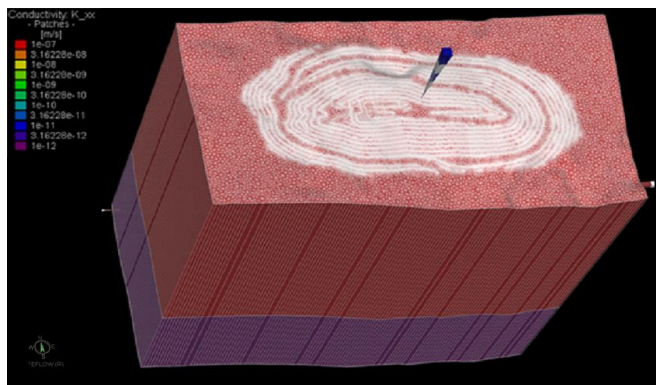


Fig - 4: The synthetic model set up with hydraulic conductivity distribution

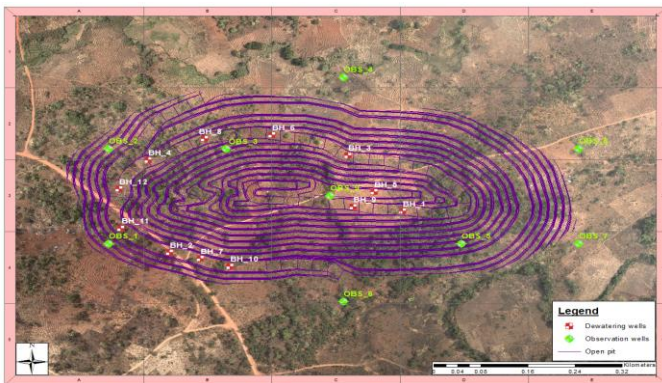


Fig - 5: Spatial distribution of observation points and dewatering well

### 2.7 Boundary conditions

The base of the model (the bottom of the shale layer) is assumed impermeable. The numerical model used in this study incorporates the following boundary conditions:

- Recharge (3 to 10% of the MAR) is represented by areal fluxes applied at the top slice of the synthetic model (the top of the dolomite layer);
- The well boundary conditions applied to the dewatering wells describes the impact of water abstraction at a single node in m<sup>3</sup>/d;

- The model assumes that the rivers and groundwater are in dynamic connection. Hydraulic head boundary condition with flow-rate constraints were used for definition of rivers.
- Constant head boundary conditions are assigned to the boundaries of the model domain. These constant heads were determined by considering the surface topography at the boundaries.

## 3. MODEL DEVELOPMENT

### 3.1 Model package

The finite element software Feflow® v6.2 from DHI-WASY was used to simulate the behavior of groundwater. Feflow is a three dimensional finite element package able to simulate unsaturated and saturated flow. It also has a mesh generation method which allows for flexible and quick editing of the model. This code allows rapid execution, development and analysis of the model (Diersch, 2004).

The capabilities of Feflow to interact with ArcGIS (ESRI) and spreadsheets is one of the important features of this software. Its flexibility is the reasons why it is one of the modelling packages preferred by scientists (Knapton, 2009).

### 3.2 Spatial discretization

The discretization of the model is done with the Feflow® package. Meshes are generated by applying the automatic triangle algorithm (Shewchuk, 2002). This algorithm is very versatile and extremely fast, and can deal with complex geometrical setups of polygons, lines, and points.

The mesh of the current model has 169 386 elements with 84 873 nodes. The regional mesh was refined in the synthetic model using the Mesh Geometry Editor. The resulting mesh used in the modelling is presented in fig-6.

### 3.3 Model settings

The synthetic model assumed saturated and unconfined conditions, and also assumed only groundwater flow (not mass transport). The total duration of the modelling was for a period of 5 months, from 01/01/2015 to 01/06/2015.

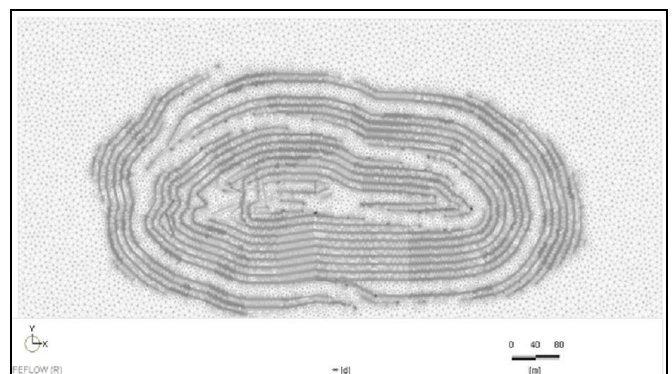


Fig - 6: Finite element mesh used in the synthetic model

### 3.4 Dewatering strategy and model results

#### a. Pre-mining groundwater levels

The natural pre-mining hydraulic gradient in the vicinity of the pit is shown in fig-7. It can be seen that under natural conditions, the groundwater generally flows from southwest to northeast within the model domain.

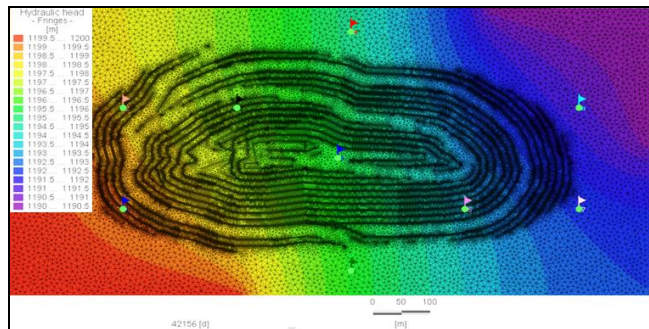


Fig - 7: Pre-mining hydraulic heads within the model domain

#### b. Static groundwater levels after mining

After excavating the pit, and allowing equilibrium (static) conditions to be reached, the bottom level of the mine is located at an elevation of 1 166 mamsl, while the highest hydraulic head within the model domain is at 1 200 mamsl.

Fig - 8 shows the water elevations in all the observation wells under static (no groundwater abstraction) conditions. As expected, all the wells display constant heads (horizontal lines), because, under static conditions, the water table is not impacted by dewatering. The difference between the highest (OBS\_1) and lowest (OBS\_9) hydraulic heads at the observation wells is 8 m within the boundary of the model, as shown in fig-8.

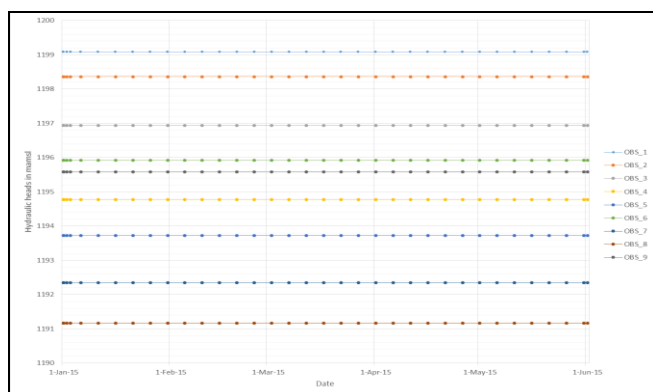


Fig - 8: Modelled hydraulic heads of the observation wells when no abstraction takes place

Under conditions of no abstraction, a pit lake occurs with a water elevation of 1 195.58 mamsl (a depth of approximately 30 m as measured from the bottom of the pit), as shown in Fig - 9.

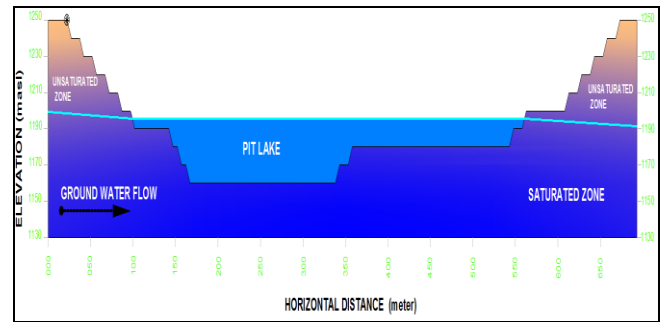


Fig - 9: East-west profile of the pit for the model at initial conditions

#### c. Dewatering using three abstraction wells

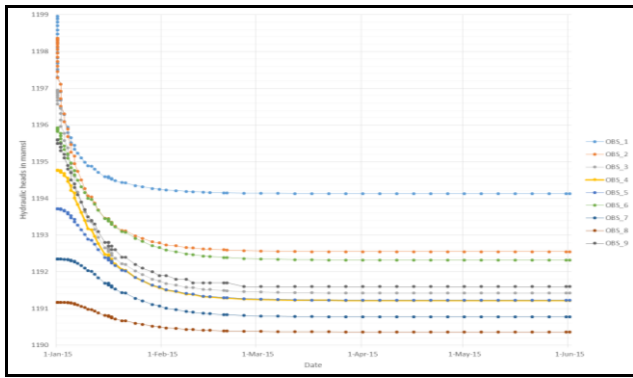
One or more dewatering strategies could be applied to lower the water level. In this research, vertical pit boreholes are used in the dewatering strategy. Each borehole pumps at a constant rate of 300 m<sup>3</sup>/h. Four scenarios, taking into account three, six, nine and 12 dewatering wells, running for a 5-month abstraction period, were considered during the modelling of pit dewatering.

To lower the water level, the first scenario consists of installing three wells (BH\_1 to BH\_3) along the isotopotometric line on the eastern ramp of the open pit in order to decrease the water inflow to the mine. After pumping commences on 01 January 2015, the water elevations at all the monitoring points decrease due to the formation of cones of depression around the abstraction wells (refer to fig-10). However, from 17 March 2015 (approximately two and a half months after pumping commenced) all observation points indicate stable water levels, as equilibrium conditions are attained.

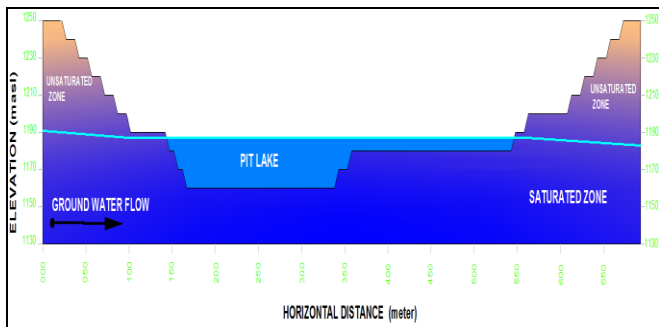
After simulating three dewatering wells pumping for 5 months, the water level in the pit lake decreased to an elevation of 1 191.6 mamsl, as shown by the fig-11. During the initial conditions, the water level at monitoring point OBS\_9 was 1 195.6 mamsl. After simulating three wells pumping for 5 months, the water level in the lake dropped by approximately 4 m. The water in the pit lake then had a depth of 26 m.

#### d. Dewatering using six abstraction wells

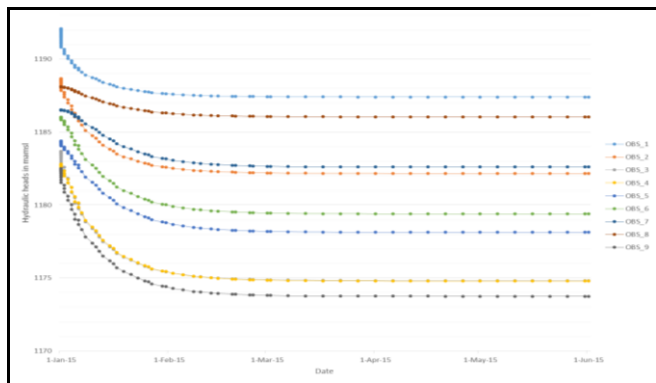
With six dewatering wells (BH\_1 to BH\_6) in the model pumping for 5 months, the depth of the water in the pit lake was reduced to 7.8 meters (observation point OBS\_9 in the pit had a water elevation of 1173.8 mamsl). The water levels in the observation wells during the 5-month period are shown in fig-12 while a cross-section through the pit showing the groundwater elevation is presented in fig-13. It can be seen that the pit is still flooded after 5 months of pumping from the six dewatering boreholes. Under these circumstances, it would therefore be difficult to re-start mining operations unless some additional dewatering wells are installed.



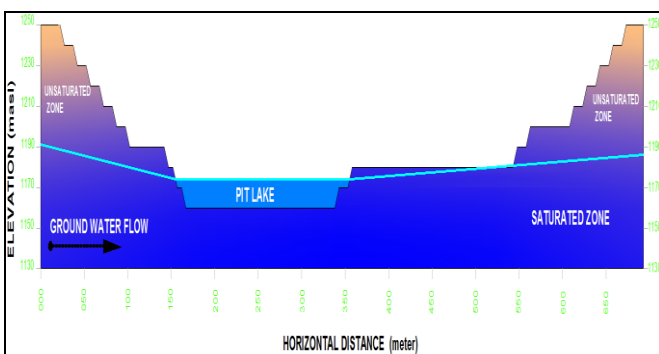
**Fig - 10:** Modelled hydraulic heads of the observation wells for the model using three dewatering wells



**Fig - 11:** East-west profile of the pit for the model using three dewatering wells



**Fig - 12:** Modelled hydraulic heads of the observation wells for the model using six dewatering wells

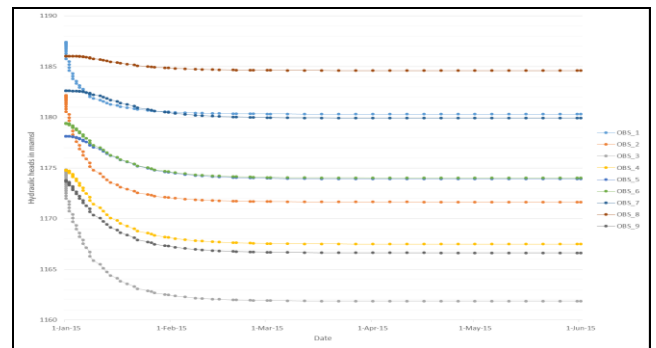


**Fig - 13:** East-west profile of the pit for the model using six dewatering wells.

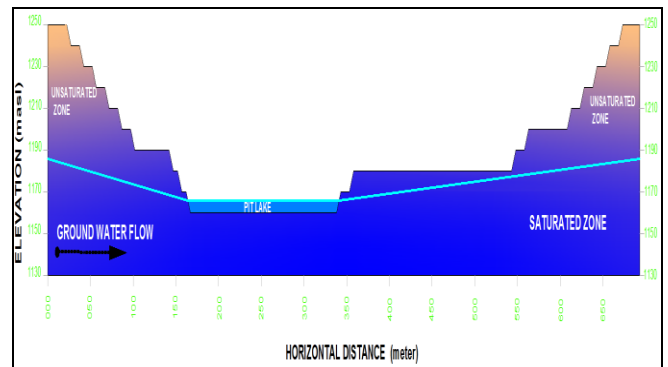
**e. Dewatering using nine abstraction wells**

The third scenario takes into account nine dewatering wells (BH\_1 to BH\_9). Abstracting water from these wells over a 5-month period reduced the water level of the pit lake (as observed at monitoring point OBS\_9) to 1166.6 mamsl. The graphs of the water levels in the observation wells (fig-14) show that the impact of the dewatering for 5 months is significant, with a steep cone of depression around the boreholes, but that the water level in the pit is not reduced enough to allow the extraction of minerals under dry conditions.

The water depth in the pit lake has now been reduced to only 0.6 meters (see fig-15). Although this water level is low, it is still not possible to extract minerals without further dewatering procedures.



**Fig - 14:** Modelled hydraulic heads of the observation wells for the model using nine dewatering wells



**Fig - 15:** East-west profile of the pit for the model using nine dewatering wells

**f. Dewatering using 12 abstraction wells**

Since nine abstraction wells were not able to dewater the pit completely, another modelling scenario with more abstraction wells is required. This scenario takes into account 12 dewatering wells to lower the water level up to one bench lower than the bottom of the pit. After 5 months of dewatering, the water level at OBS\_9 in the pit stabilizes at 1151.2 mamsl (refer to fig-16). This elevation is 14.8 m below the bottom elevation of the pit floor.

A cross-section through the pit after 5 months of pumping with 12 abstraction wells is shown in fig-17 The groundwater level is now below the bottom of the pit and the extraction of minerals can commence.

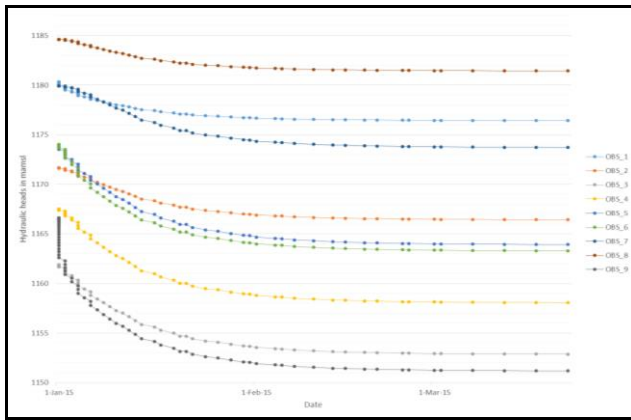


Fig - 16: Modelled hydraulic heads of the observation wells for the model using 12 dewatering wells

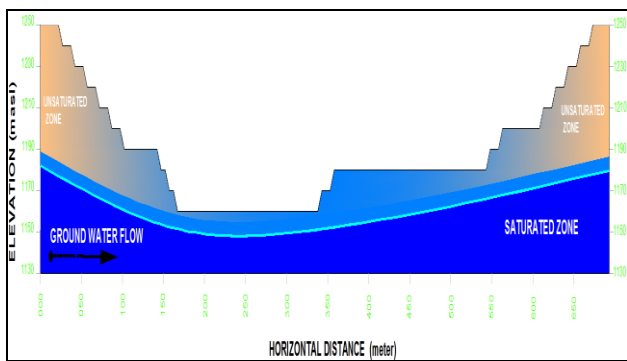


Fig - 17: East-west profile of the pit for the model using 12 dewatering wells

#### 4. DISCUSSION AND CONCLUSION

In Fig - 18, the results of the different modelling scenarios are summarized by plotting the pit water level (OBS\_9) against the number of abstraction wells used in the dewatering strategy. From this figure, it is clear that the different modelling scenarios had significantly different impacts on the groundwater and pit water levels. The model results also showed under which conditions complete dewatering of the pit will be attained.

The model results provide valuable datasets of hydraulics heads measured against time for the different pumping scenarios. These synthetic data sets can be used for numerous purposes in hydrogeology and geotechnical engineering such as training, testing and validating Artificial Neural Networks for mining operation purposes.

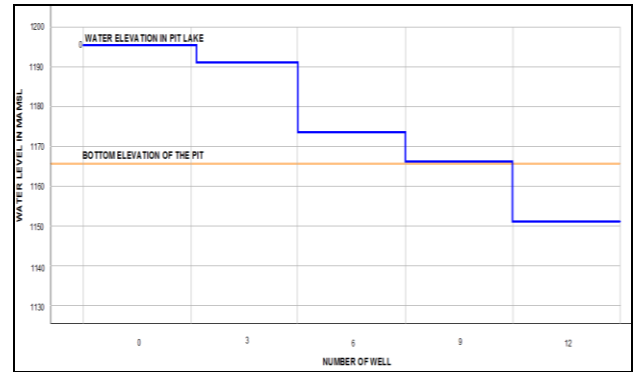


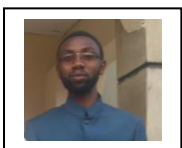
Fig - 18: Summary of the dewatering impact relative to the bottom of the pit

#### REFERENCES

- [1] F. Abdulla, M. Al-Khatib, Z. Al-Ghazzawi, "Development of groundwater modeling for the AZROQ basin", *Environ Geol.* 40(1/2):11-18, 2000.
- [2] M. Anderson and W. Woessner, "Applied Groundwater Modeling, Simulation of Flow and Convective Transport", Academic San Diego, California, 1991.
- [3] K. Anthony, "An integrated surface - groundwater model of the Roper River Catchment, Northern Territory", dept. of Natural resources, Env. Art and Sport, Australian gov. 69 p., 2009.
- [4] M. Bakker, "Simulating groundwater flow in multi aquifer systems with analytical and numerical Dupuit models", *J. Hydrol.* 222, 55-64, 1999.
- [5] Carslaw and Jaeger, "Conduction of Heat in Solids. Oxford University", 1959.
- [6] P. Domenico and F. Schwartz, "Physical and chemical hydrogeology", second Edition, Wiley, 1998.
- [7] FemLab User Guide, "An introduction to FEMLAB's Multiphysics modeling capabilities", Burlington, 40p. 2015.
- [8] P. France, "Finite element analysis of three dimensional groundwater flow problems", *J. Hydrol.* , 21, 381-398, 1974.
- [9] M. Heinl and P. Brinkmann, "A groundwater model of the Nubian aquifer system", *Hydrol. Sci. J.*, 34:425-447, 1989.
- [10] H. Karahan and M. Ayvaz, "Transient groundwater modeling using spreadsheets", *Adv. Eng. Software:* 36, 374-384, 2005.

- [11] H. Karahan and M. Ayvaz, "Time-Dependent Groundwater Modeling Using Spreadsheet", Computer applications in engineering education: 13, 192 -199, 2005.
- [12] L. Kipata, "Brittle tectonics in the Lufilian foldand- thrust belt and its foreland An insight into the stress field record in relation to moving plates (Katanga, DRC)", PhD thesis KU Leuven, faculty of science, p.160, 2013.
- [13] D. Morris and A. Johnson, "Summary of hydrologic and physical properties of rock and soil materials as analyzed by the Hydrologic Laboratory of the U.S. Geological Survey", U.S. Geological Survey Water-Supply Paper 1839-D, 42p., 1967.
- [14] J. Shewchuk, "Delaunay refinement algorithms for triangular mesh generation", Computational geometry: theory and application, Amsterdam, Volume 22: 21-74, 2002.
- [15] P. Wang and M. Anderson, "Introduction to Groundwater Modeling", W. H. Freeman and Company, San Francisco. 237 pp., 1982.
- [16] P. Wang and Z. Chunmaio, "An efficient approach for successively perturbed groundwater models", Adv. Water Res., 21: 499-508, 1998.
- [17] T. Winter, "The concept of hydrologic landscapes", J. Am. Water Resources Assoc.: 37:335-349, 2001.
- [18] W. Woessner and M. Anderson, "The hydro-malapropos and the ground water table", Ground Water, vol. 40, no. 5, p. 465, 2002.

## BIOGRAPHIE



Sage Ngoie was born in Democratic Republic of Congo. He obtained a degree in Geology and a Master's Degree in Geotechnical and Hydrogeological Sciences. He holds a PhD in Geohydrology from the University of the Free State in South Africa where he specialized in Artificial intelligence and mathematical modeling applied to groundwater.