Predicting Pit Lake Formation and Water Quality

David Arcos, Jordi Guimerà, Salvador Jordana, Eduardo Ruiz and Jorge Molinero
Amphos 21 Consulting, Spain

ABSTRACT

Pit lakes form when open pit mining operations are discontinued and dewatering ceases. The resulting composition of the water within the lake is related to the geology and mineralogy of pit walls, water flow rates and climate conditions. In some cases, these lakes will develop acid sulphate conditions with high concentrations of metals, thus constituting an environmental concern. Preventing such conditions from the early stages of the mine project allows a proper planning for mine closure, yet conditions can be predicted, allowing taking informed decisions.

In this work, open pit flooding has been simulated using COMSOL Multiphysics, a well-known commercial FEM platform, and water quality can be calculated by coupling the geochemical code PHREEQC code with the Java interface iCP. In the implemented model the height of the lake depends on the relationships between the groundwater water inflow rate of the lake, the elevation of the spillway, the water volume of the lake as a function of the height of the water and the evaporation rate. In its turn, the height of the lake variable is used as a Dirichlet boundary condition at the bottom of the open pit in a realistic hydrogeological large-scale 3D aquifer. The water quality can be determined by considering the geochemical processes in the interaction of water with the pit walls, as well as by considering the contribution from rainwater and the evaporation effect.

The resulting model is able to recreate transient pit lake generation and water quality. The simulations predict the rise of water in the pit lake as a function of time, the maximum elevation of the lake and the flow rate of the creek that could appear by overflow if the lake reaches the pit boundary. In terms of water quality, the simulation is able to predict the composition evolution with time of both the water entering into the lake and the lake itself, even after reaching a hydraulic stationary state. Results obtained show a good agreement with currently available field data. It is worth mentioning that the model could also calculate lake stratification due to thermal and/or ionic strength effects, although it has not been implemented yet.

Keywords: Pit lake, mine closure, modelling, hydrogeology, geochemistry.

INTRODUCTION

Excavated pits can have several depths and sizes, but all of them require environmental reclamation. One possible reclamation endpoint could be the creation of pit lakes (Gammons et al., 1999). Pit lakes are created by filling by water the open pit left after the completion of mining operations. This water filling can be done by artificial flooding or natural hydrological processes such as rain or groundwater inflow (Castro and Moore, 2000).

The increase in open-pit metal mining since the 1970s will lead to the formation of numerous pit lakes over the next 50 years. Many of these lakes could develop acid sulphate conditions with high levels of dissolved metals. Recommended approaches for remediation of these conditions include the addition of lime or other alkaline materials and the stimulation of sulphate-reducing bacteria. However, prevention rather than remediation is probably the preferable approach. Measures, like filling the pits with water as fast as possible to promote anoxic conditions within the lake preventing the oxidation of sulphides present in the pit walls, thus minimizing the formation of acids and dissolved metals (Castro and Moore, 2000).

Local hydrogeology determines how fast an open pit lake is formed in natural conditions. A generalized water balance for a pit lake can be summarized as the change in water storage in the lake, which results from the addition of inflows (direct rain, surface water runoff and streams, and groundwater inflow) and the subtraction of the outflows (evaporation, groundwater outflow, surface water outflow as a creek from the lake). The rate of groundwater input depends on the site geology, topography and climate. A rough estimate of groundwater inflow can be obtained by looking at the amount of water that was pumped during active mining operations. This can provide a useful estimation during the early stages of flooding but the rate will change as the pit fills with water and the hydraulic gradient towards the lake will decrease. On this context, water quality will be the result of the interaction of groundwater with the pit walls, especially to a depth where atmospheric oxygen can penetrate. Considering that flow rates decrease as water level rises and that sulphide oxidation reactions are kinetically driven, the quality of the inflow water will be worst with time. Thus, the quality of the water in the lake is dependent on the velocity of lake formation. In addition, other aspects that may affect water quality are the surrounding groundwater composition, the amount of rainwater (and/or evaporation) and the characteristics of the pit walls (sulphide amount and distribution).

Once a pit lake has been filled to its ultimate surface elevation, there are many different hydrogeological scenarios for the lake, which can be considered important factors for "end use" decisions. For example, in an arid climate, it is very possible that evaporation will completely balance any water input terms. Such a lake is referred to as a "terminal" lake. A "flow-through" lake, on the other hand, will receive groundwater inputs from one side, but will lose groundwater to the other side. Flow-through lakes are especially common when the pit was excavated on a hillside with an initially sloping water table. Finally, if water inputs are high (such as in a wet climate, or where a stream is permanently diverted into the lake), then the final lake will probably have a surface water output. This could either be an engineered spillway or stream (Gammons et al., 2000). The effect on the water quality is also dependent on the behaviour of the lake once it reaches the ultimate surface elevation. In an arid climate, the excess evaporation will result in increasing the concentration of sulphate and metals in the water lake (Atkinson, 2002), resulting in the precipitation of sulphate minerals in the lakeshore. In "flow-through" lakes, the quality of the water will depend on the quality of entering groundwater, thus good quality groundwater will result in improvement of the lake quality. Finally, in wet climate conditions, it could be expected that dilution result in increasing the quality of the water in the lake. Another aspect that must be considered is the role of emerged pit walls; if the amount of sulphides present is high, surface run-off can affect negatively the water quality in the lake, although tis effect needs to be assessed carefully.

To quantitatively approach pit lake formation and water quality, preliminary conceptual models are typically developed by: 1) compiling all available data (geologic, mineralogical, climatic, potentiometric, hydraulic testing, etc.); 2) evaluating the data to determine aquifer geometries, hydraulic boundaries, hydraulic parameters, groundwater movement, geochemical processes and other variables of interest; and 3) integrating this information into one or more working hypotheses that characterize the system.

Numerical simulations allow the validation of the conceptual models, as well as the quantification of the predicted effects on the pit lake, such as inflow and outflow rates, water quality and their dependency with time. To model this groundwater flow-lake system some specific modules as PITLAKE, LAKE, LAK2 (Moreno and Sinton, 2002) have been created for MODFLOW.

In this paper we will simulate this transient pit lake generation using COMSOL Multiphysics® (COMSOL, 2012). COMSOL provides generic partial differential equation (PDE) solvers and Algebraic Differential Equations (ADE) that are robust in handling coupled equations. COMSOL has developed several modules helpful for hydrologic applications, e.g., the Subsurface flow modules (COMSOL, 2012). However, singular implementations as the pit lake generation must be explicitly user defined. The geochemical processes are implemented with the PHREEQC code (Parkhurst and Appelo, 2013), which is coupled with COMSOL by means of iCP, a Java interface (Nardi et al., 2014).

METHODOLOGY

Groundwater system

The groundwater system is described by the flow equation (Bear, 1979), (nomenclature for all formulas can be found at the end of this publication):

$$S_e \frac{\partial p}{\partial t} = -\nabla q + Q \tag{1}$$

where the Darcy's flow (q) can be expressed by Darcy's law:

$$q = -K\left(\nabla p - \rho g\right) \tag{2}$$

Figure 1 shows a sketch of the hydrogeological system in the problem of interest.

The chemical part of the system is calculated through the code PHREEQC. One of the main aspects is related to the penetration depth of atmospheric oxygen ($10^{-0.67}$ bars partial pressure) into the rock in the unsaturated region, allowing the water to equilibrate with this oxygen pressure. In this zone sulphide oxidation can occur, so the primary minerals able to react are considered in the system allowing their dissolution following a kinetic rate. Secondary minerals are allowed to precipitate if they become supersaturated. Aqueous speciation is specifically considered in the code. Other geochemical processes such as sorption, cation exchange or solid solution precipitation can also be included in the calculations if needed. One important aspect is that mineral distribution in the rocks around the pit is not uniform. Therefore, based on geochemical data and block model the mineral distribution in the system can be defined (Figure 2), allowing the definition of different mineral zones depending on their mineral content.

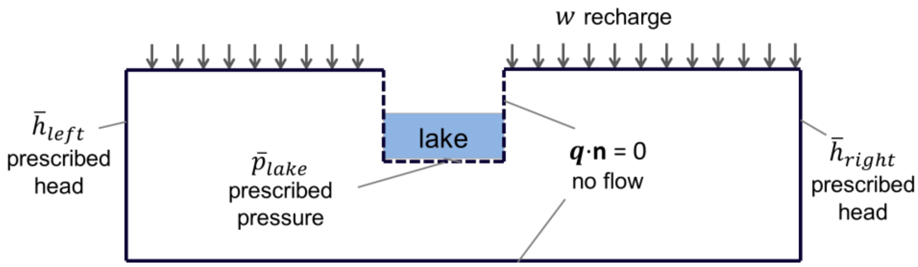

Figure 1 Sketch of the hydrogeological system in a synthetic problem

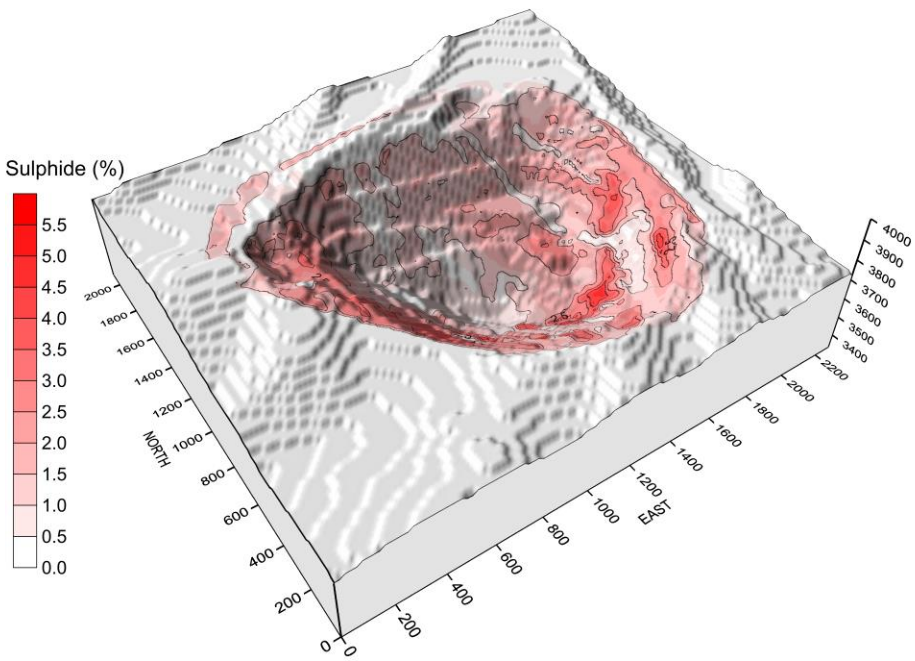

Figure 2 Sulphide distribution in the wall of a final open pit

Lake system

The volume water balance in the lake is described by:

$$\frac{d\left(V_{lake}\right)}{dt} = Q_{aq} - Q_{ev} + Q_r \tag{3}$$

The net groundwater flow rate from the aquifer to the lake is expressed by:

$$Q_{aq} = \int_{A_{\min}} \left(q \cdot n\right) dA \tag{4}$$

The evaporation outflow rate is calculated as:

$$Q_{ev} = E \cdot A_{lake} \tag{5}$$

The rain inflow rate is calculated as:

$$Q_r = w \cdot A_{lake} \tag{6}$$

Note that for simplicity here we only consider the rain that impacts straightforward to the lake surface, not the total of the lake hydrologic basin, but the model could also handle this condition with minor changes. Figure 3 shows the sketch of the lake system analysed in this problem.

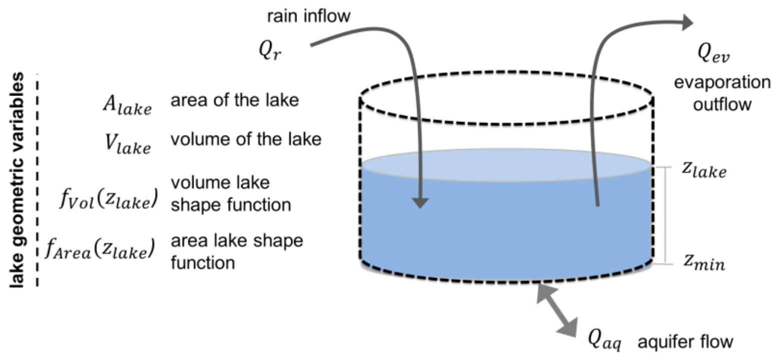

Figure 3 Sketch of the lake system in a synthetic problem

As in the case of the groundwater system, the interaction between lake water and mineral zones in the pit walls can occur. In this case the reactions are limited to the water in contact with the pit wall and sulphide oxidation is restricted to the near surface zone, where water with enough oxygen dissolved can be found. In addition to secondary minerals precipitated due to the water – rock interaction, they can also precipitate near the surface due to evaporation processes. However, this effect has not been implemented yet.

Analysis of the coupling used between underground and surface water

The groundwater and the lake system are coupled in both directions by the following terms (Figure 4):

- Equation 4 couples the lake system with the groundwater by means of the aquifer flow rate.
- The underground system is coupled by the Dirichlet boundary condition applied at the bottom of the lake,

$$\bar{p}_{lake} = \rho g z_{lake} \tag{7}$$

The natural evolution of the system tends to a steady state situation where the lake level is constant and the groundwater inflow rate is equal to the evaporation rate (Figure 5).

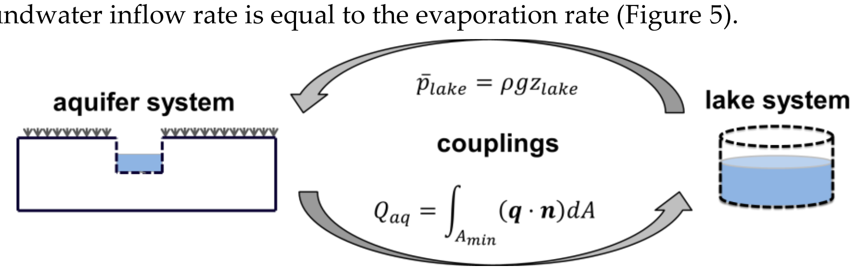

Figure 4 Couplings between the aquifer and the lake system

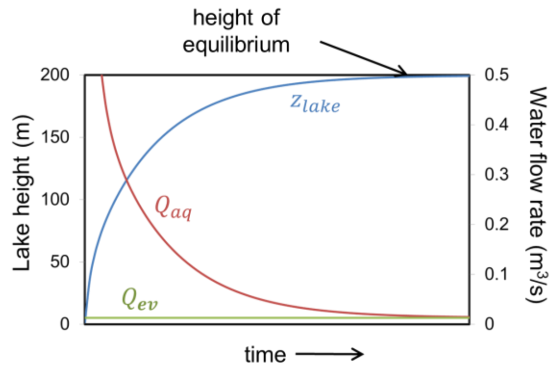

Figure 5 Expected behaviour of the system

This coupled problem has been solved by performing a Picard approach, solving the lake and the aquifer system iteratively until the solution has converged. The nonlinear system of equations of the lake has been solved by using a Newton-Raphson algorithm.

APPLICATION CASE

A pit lake generation in an open pit mine has been simulated using the abovementioned equation system. The mine, located in a temperate climate area, stopped the dewatering at the beginning of the 2000. Before that, the maximum dewatering flow rate was about 20 l/s.

The mine is placed onto a natural water divide and the topography has a gentle slope to both sides. The geology consists on a fractured crystalline rock with a significant alteration zone in the uppermost part. This shallow part formed mainly by sand, has a thickness of a few meters and constitutes the main aquifer (Figure 6).

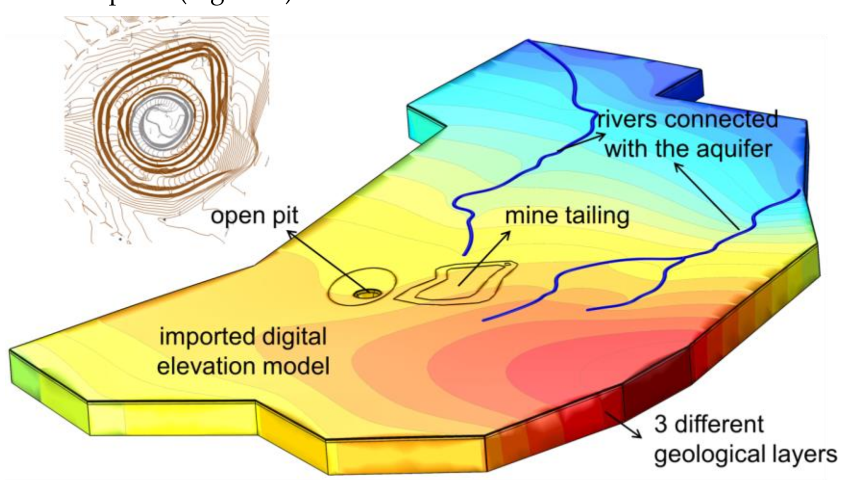

Figure 6 Hydraulic head distribution

Streams and creeks occur in the lowest areas. These streams flow permanently and have been set as fixed head (Dirichlet) boundary condition. Internal streams are ephemeral and they have been modelled by a mixed flow (Cauchy) condition. The upstream boundary, the highest one, has been considered as a prescribed head boundary, using available piezometric data. Remaining boundaries are considered impervious (no flow Neumann condition). Water recharge of 150 mm/y is prescribed on the top boundary, to account for infiltration of rainwater.

The final pit wall has been divided in geoenvironmental units (GEUs) according to the mineral contents, especially sulphides, and their geochemical behaviour based on previous geochemical tests (Table 1 and Figure 7). The primary minerals have been considered to dissolve following a kinetic rate. The reactive surface area of these minerals has been calculated based on rock porosity and assuming that water flows through fractures with a mean aperture of 0.02 mm. In this way, the rock surface in contact with a litre of water has been calculated, and then distributed between the different minerals according to their relative amount in the rock (Table 7). Secondary minerals are allowed to precipitate when they become supersaturated both in the rock (groundwater system) and in the lake (lake system). Other processes can be implemented, such as sorption or cation exchange, but they have not been considered in this case. In addition, the possibility of considering stratification of lake water due to ionic strength and temperature has not been considered. According to the COMSOL capabilities, it is possible to include this process in the model, but it has not tested yet.

Modelling stages were the following:

- Steady state flow model to simulate the conditions at the end of the period of activity of the mine. In this phase, the hydrodynamic parameters have been adjusted to fit site observations: the pumping dewatering rate and piezometer levels. During this stage the lake system is not active and a fixed head equals to the topographic value (zero pressure condition) has been considered at the bottom of the open pit.
- Transient model. The result of the steady state model of the previous stage has been used as initial conditions. At this stage the full system (lake and groundwater) is accounted to simulate the open pit lake generation.

In both stages the chemical composition of lake water depends on the geochemical processes occurring in:

- Pit walls: interaction of groundwater with defined GEUs; and
- Lake: water resulting from pit wall seepage and mixing with already existing lake water and rainwater, plus effects of evaporation.

Table 1 Mineral composition of the GEUs defined for the pit walls.

Minerals (wt %)	GEU 1	GEU 2	GEU 3	GEU 4
Pyrite	0.1	0.5	2.0	5.5
Chalcopyrite	0.0	0.02	0.1	0.7
Arsenopyrite	0.0	0.01	0.05	0.1
Sphalerite	0.0	0.01	0.03	0.2
Fe(III) oxides	0.1	0.5	0.5	2.5
Quartz	57	56	58	55
K-Feldspar	20	17	12	16
Biotite	0.8	0.8	0,5	0.8
Clay minerals	21	25	26	19

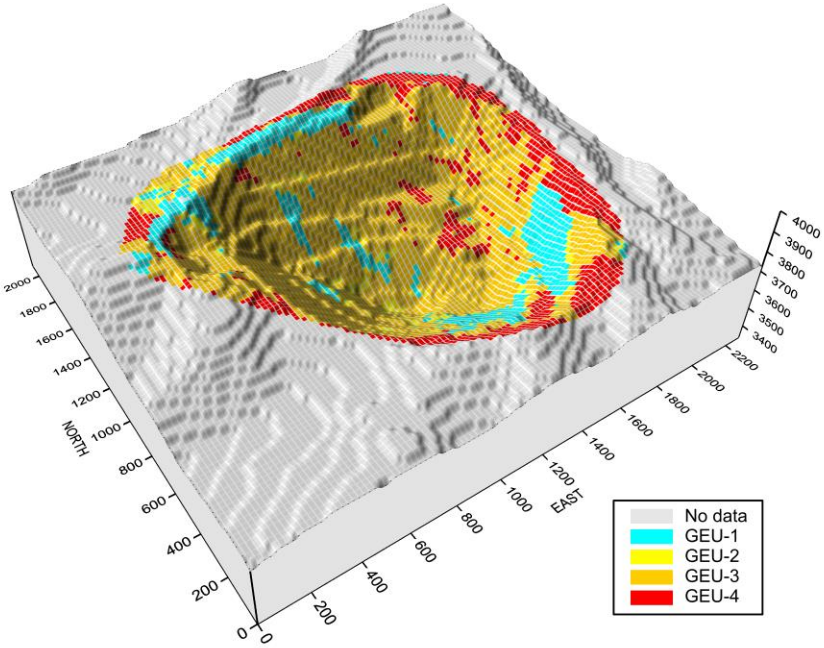

Figure 7 Distribution of geoenvironmental units (GEUs) in the final pit walls.

The domain has been meshed by means of nearly 700.000 tetrahedral quadratic elements. To improve the time and the accuracy of the non-linear calculation process the time steps and numerical convergence parameters has been adjusted for the transient simulation. In terms of chemical composition, it can be seen (Figure 9), that for the first 10 years of evolution (up to present) a major impact is not expected. However, after this time, it is expected that lake water became gradually more and more acidic and with higher metal concentrations.

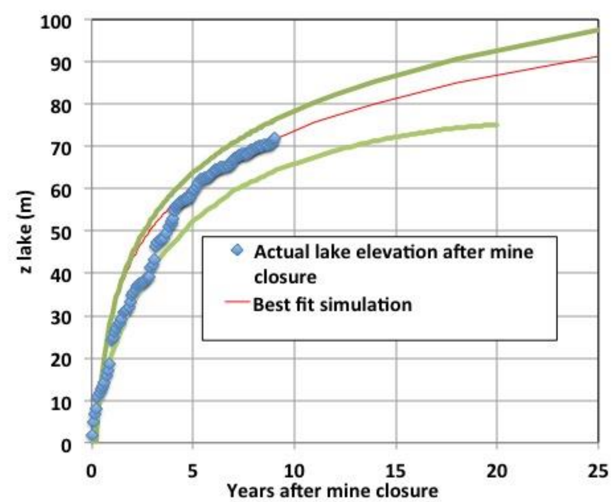

Figure 8 Sensitivity analysis (green lines) has shown permeability and storativity as most critical parameters for an accurate prediction

The mine operation counts with about 10 years of observation data available from the beginning of water rise in the open pit. These data have been used to calibrate the model and the best fit obtained reproduces satisfactorily the growth of the lake. A sensitivity analysis showed that the response of lake level rise is very sensitive to the hydraulic parameters of the aquifer, to the recharge and evaporation rates and to open pit geometry (Figure 8).

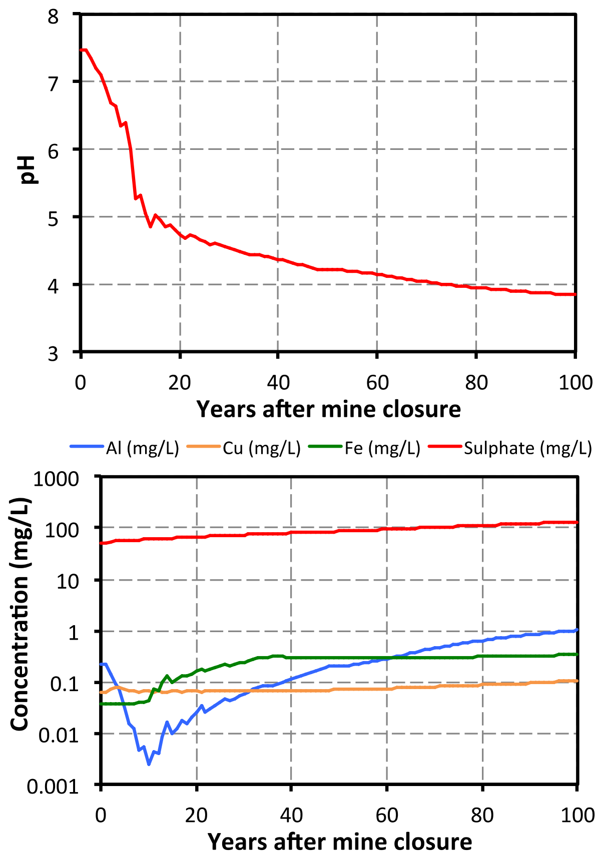

Figure 9 Predicted chemical evolution of the lake water.

For this particular mine, the computed results allows to conclude that at the final stages the lake will be a "flow-through" lake and also will eventually generate a stream through a spillway. All these results are very important for the management of effluents as they may be affected by old mining activities and may affect the environment.

CONCLUSION

The pit lake dynamics and quality can be modelled by the groundwater and lake coupled system developed in this work, as well as coupling hydrologic and geochmemistry processes. This system has been used in a real case and it reproduces satisfactorily the growth of the lake according the available data and predicts present and future water lake composition.

One of the most powerful aspects of the proposed formulation is its flexibility. The developed simulator admits all kind of open pit geometries since it is generalized for area and volume lake shape functions. In addition, other sources and sinks (even nonlinear ones) can be added easily in the lake water balance.

Important information that can be predicted by using this model is:

- The flow rate for dewatering and the lake height after closure,
- the time to generate a creek (if any) and its flow

- the lake and groundwater flow relationship: flow- through or terminal.
- the lake water composition, and its expected evolution with time.

The model presented in this paper constitutes a powerful pit lake prediction, especially when the environmental conditions claim for high accuracy.

NOMENCLATURE

A_{lake}	area of the lake (m^2)
A_{min}	minimum area of the lake (m^2)
E	evaporation rate ($m \cdot s^{-1}$)
g	gravity vector ($m \cdot s^{-2}$)
K	hydraulic conductivity tensor ($m \cdot s^{-1}$)
p	liquid pressure (Pa)
Q	source term ($m^3 \cdot s^{-1}$)
Q_{aq}	flow rate to the lake from groundwater ($m^3 \cdot s^{-1}$)
Q_{ev}	evaporation rate ($m^3 \cdot s^{-1}$)
Q_r	rain inflow rate ($m^3 \cdot s^{-1}$)
q	Darcy's flow ($m^3 \cdot m^{-2} \cdot s^{-1}$)
S_e	specific storage (m^{-1})
V_{lake}	Volume of the lake (m^3)
w	rain rate ($m \cdot s^{-1}$)
ρ	liquid density ($kg \cdot m^{-3}$)

REFERENCES

Atkinson, L.C. (2002) *The hydrology of pit lakes*. Southwest Hydrology, 1(3).

Bear, J. (1979) *Hydraulics of groundwater*. McGraw-Hill International Book Co., 1979 - 567 p.

Castro, J.M. and Moore, J.N. (2000) *Pit lakes: Their characteristics and the potential for their remediation*. Environ. Geol. 39, pp. 1254-1260.

COMSOL (2012) *COMSOL Multiphysics 4.3*. Viewed at www.comsol.com

Gammons, CH., Harris, L.N., Castro J.M., Cott, P.A. and Hanna, B.W. (2009) *Creating lakes from open pit mines: Processes and considerations – with emphasis on northern environments*. Can. Tech. Rep. Fish. Aquat. Sci. 2826: ix + 106 p.

Moreno, J. and Sinton, P. (2002) *Modeling mine pit lakes*. Southwest Hydrology, 1(3).

Nardi, A., Idiart, A., Trinchero, P., deVries, L.M. and Molinero, J. (2014) *Interface COMSOL-PHREEQC (iCP), an efficient numerical framework for the solution of coupled multiphysics and geochemistry*. Computers & Geosciences 6910–21.

Parkhurst, D. L. and Appelo, C. A. J. (2013) *Description of input and examples for PHREEQC version 3—A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations*. USGS Techniques and Methods, book 6, chap. A43, 497 pp.