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GROUNDWATER INFLOW MODELING FOR A KAZAKHSTAN COPPER ORE DEPOSIT

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Mining exploration is widely spread throughout Kazakhstan and it is an important part of the country's economy. However, mining can create landslides, as well as both surface and groundwater pollution. The purpose of this research is to model the water movement and water volume changes for one of Kazakhstan's mining operations. In this study, we have modeled and predicted the water volume changes within a mining operation for the next 50 years, until the year 2065. The sulphide-ore mining operation, which was studied, is located in East Kazakhstan. Several mining development scenarios with groundwater volume changes were prepared. One of the modeling scenarios was related to the mining pit exploration up to a depth of 100 meters. The groundwater inflow was computed at 106.3 m^3/hour, or 2551.6 m^3/day for this scenario. Another modeling scenario for the same mining pit had a depth at 585 meters. The groundwater inflow for this scenario was computed at 268.6 m^3/hour, or 6447.3 m^3/day. Calibration and verification were provided for the modeling work, and results were compared to the water balance. The results of this work could be considered for the engineering design to drain the groundwater from the mining pit. This research work and methodology are replicable and could be applied to other mining explorations and groundwater inflow prediction analyses. The methodology can be adapted to open pit mines under similar conditions.

INTRODUCTION

Open pit quarries influence surface and underground drainage and groundwater movement. The quarries affect water inflow conditions into a mining pit, and the connected watershed and river flow. The open mining pit operations at open pit quarries disturb the natural surface and groundwater movements which create hazards that can negatively impact, flora, fauna, as well as human life within the affected watershed. Therefore, understanding water movement, including water inflow to the quarry, is an integral part of effective quarry operation and management (Martinez and Ugorets, 2010). For the elimination of hazards, the following project stages should be under permanent improvement: (a) water inflow prediction analyses, (b) proper engineering design to reduce the water inflow to the mines, and (c) emergency design and backup options for pit dewatering modes (borehole patterns) (Peksezer-Sayit and Cankara-Kadioglu 2014, Surinaidu et al. 2014, Surinaidu et al. 2011, Yang et al. 2011). Engineering mine construction works are very expensive; hence, the proper modeling and prediction analyses are critical for any mining activities. Moreover, with climate change, the water fluctuations and complexity related to water production will increase every year (Song et al., 2014). Mining hydrological conditions should be studied properly to avoid future landslides and dangerous water inflow (Mnzool et al., 2015). Landslides are typical geological disasters that also pose considerable hazards to both humans and the environment (Matsushi, 2012, and Wei, 2006). Landslides may occur at mining deposits (Ataei, 2008); therefore, prediction analyses and modeling are important for the permanent improvement of disaster risk reduction (henceforth DRR) (Brown and Trott, 2014). The model provides a consistent quantitative framework with which new tests or operations can be evaluated in a cost effective manner (Paulino Fernandez-Alvarez, 2015). The purpose of this research is to model the water movement and water volume changes for one of Kazakhstan's mining operations.

MATERIALS AND METHODS

Input data

Initial input data for the research were collected from previous hydrogeological and geological studies. The research area is the Aktogay sulphide-ore deposit, which is located in East Kazakhstan at the junction of the Central Kazakhstan fold-mountain area, and the Alakul inter mountain plain (Figure 1) (Kydyrbekov and Shtyfanov, 1976). The Aktogay copper deposit is planned to be an open mining exploration pit with a maximum length of 2,750 meters, width of 2,500 meters, and depth of 585 meters. The open mining pit area is approximately 5-square kilometers. The mining deposit is planned for exploration for the next 50 years, until 2065. The mining deposit area is a fractured zone of solid Paleozoic rock in an area of spot groundwater recharge and transit (Yerikuly, 2014). The upper deposit area is under high water inflow occurring down to a depth of 90 meters (Zhaparhanov and Yerikuly, 2012). The deposit rock hydraulic conductivity varies from 0.025 to 0.41 meters per day, while the average hydraulic conductivity is at 0.17 meters per day (Yerikuly, 2014). The water penetrations were traced through the fractured rock to a depth of 220 meters. Water inflow and the deposit rock hydraulic conductivity decrease with depth. Average deposit hydraulic conductivity within the interval of 90-585 meters is 0.016 meters per day. The average deposit rock specific yield is 0.007 (Yerikuly, 2014). The main water source to the mining deposits is atmospheric precipitation. The average long-term yearly atmospheric precipitation level in the deposit area is 194 mm. The maximum yearly precipitation was 290 mm, which occurred in 1957 (Abramov, 1968). The evaporation level is high as compared with the small level of transpiration in the research area. The water balance was calculated, and a discharge to the mining deposit groundwater was computed (Zhaparhanov and Yerikuly, 2012).

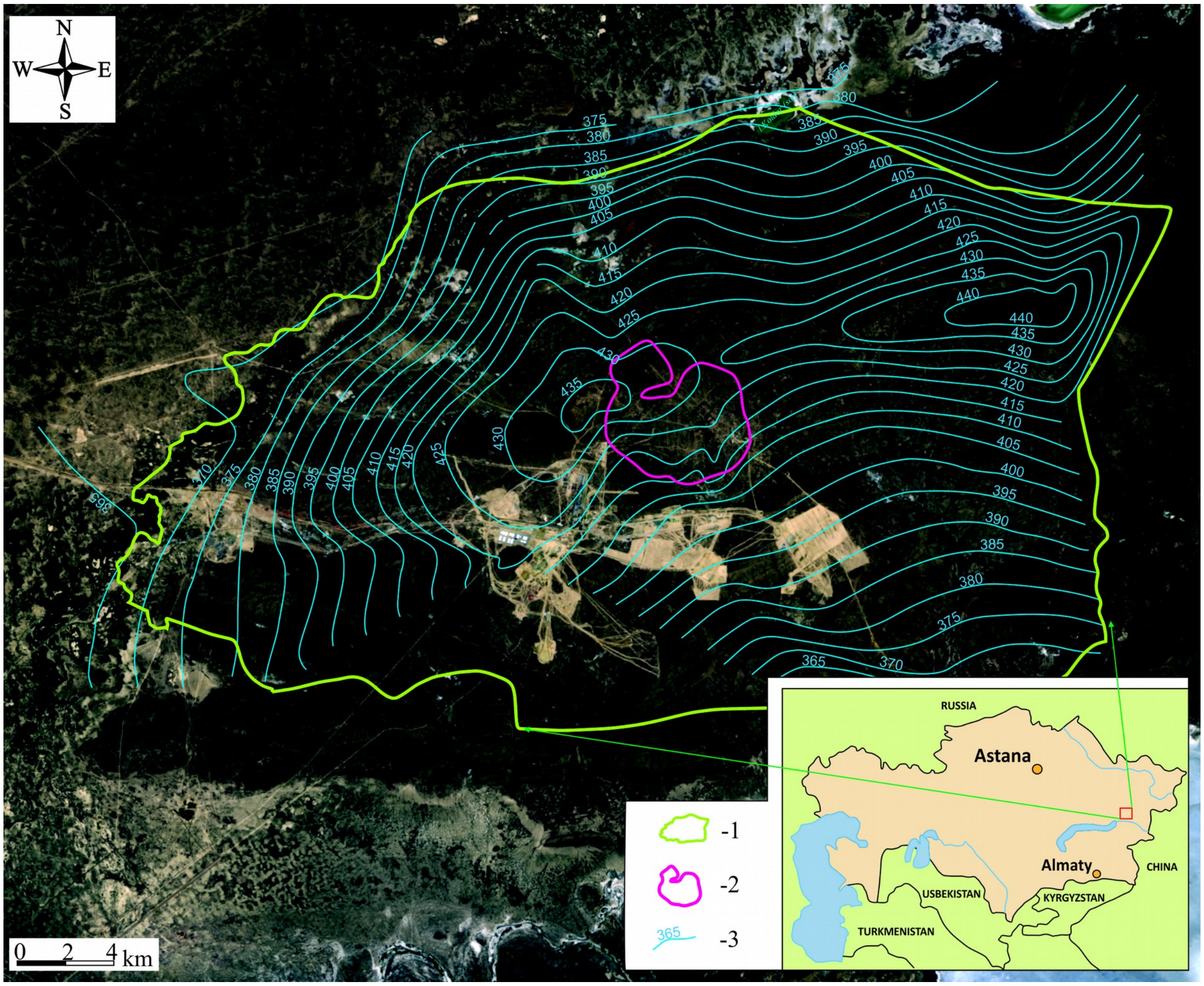

Figure 1. Location of the open pit (1) Model outline, (2) Pit outline, (3) Hydroisobaths of the first from the surface aquifer. Figures are absolute elevations of hydro-isobaths

Geology and data preparation for modeling

The fault lines of Main Koldarsk, Zhuzagach-Koldarsk, and Kylyjsk were reviewed for the model outlines (Figure 2). The open pit outline is located in the central modeling area (Figure 2). The external boundaries are located at a sufficient distance from the pit outline to minimize the impact on the hydrogeological processes of the pit. External boundaries are schematized with boundary conditions of the first type (Figure 2). The pit area is schematized with boundary conditions of the second type (Figure 2) (Babushkyn and Lebedyanskaya, 1971). Four layers are distinguished in the cross-section depending on the water content (Figure 2). The first layer corresponds to water-bearing rocks. The bottom of the second layer lies at the border of the depositary with flooded fractures.

Most of the third layer is made up of water-free rocks with low hydraulic conductivity. The fourth layer is impermeable rock (Figure 2) (Herrera and Garfias, 2013). To estimate water inflow at the Aktogay deposit, we used a flow filtration equation for ground water under heterogeneous and anisotropic conditions.

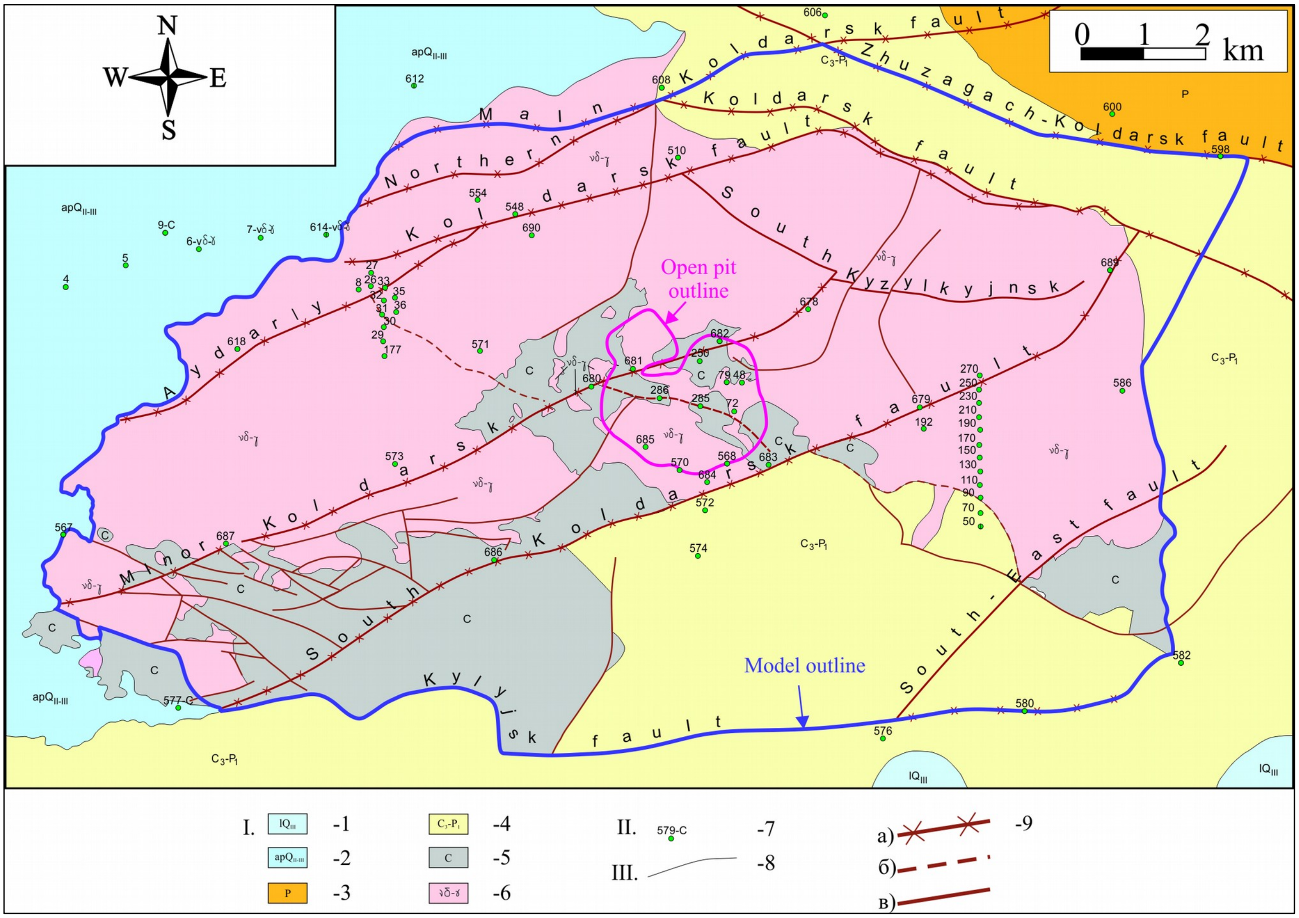

Figure 2. Model outline I. (1) Aquifer of the Upper Quaternary lacustrine deposits, (2) Aquifer of the Mid-and Upper Quaternary alluvial and pluvial deposits, (3) Ground water in the open fracturing zone of the Permian deposits, (4) Ground water in the open fracturing zone of the undivided Upper Carbon and Low Permian deposits, (5) Ground water in the open fracturing zone of the Carbon deposits, (6) Ground water in the open fracturing zone of the intrusive acid and medium rocks of different ages. II. Water points. (7) Borehole, figures on top signify the borehole number and index. III. Other symbols, (8) Aquifer borders, (9) Fractures: a) water-bearing, b) water-free, c) hydrological condition was not defined

Three dimensional stationary flow filtrations can be described with the following equation:

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})-W=0 \tag{1}$$

under initial conditions

$$h(x,y,z)=H_0(x,y,z) \qquad at\ \Omega$$

under boundary conditions

$$h(x,y,z)=H(x,y,z) \qquad at\ \Gamma_1$$

$$K_n\frac{\partial h(x,y,z)}{\partial n}=Q(x,y,z) \qquad at\ \Gamma_2$$

Three dimensional non-stationary flow filtrations can be described with the following equation:

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})-W=S_s\frac{\partial h}{\partial t} \qquad (2)$$

under initial conditions

$$h(x,y,z,t)=H_0(x,y,z) \qquad at\ \Omega, t=0$$

under boundary conditions

$$h(x,y,z,t)=H(x,y,z,t) \qquad at\ \Gamma_1, t\geq 0$$

$$K_n\frac{\partial h(x,y,z,t)}{\partial n}=Q(x,y,z,t) \qquad at\ \Gamma_2, t\geq 0$$

where K_{xx}, K_{yy}, K_{zz} – hydraulic conductivity towards coordinate axis *x, y* and *z* (Lt^{-1});

h – head (L);

W – volume flow per unit of volume, which represents water sources and/or flows (t^{-1});

S_s – specific yield of porous material (L-*1*);

t – time (t);

In general, the functions S_s, K_{xx}, K_{yy}, K_{zz} can be the functions of spatial coordinates ($S_s = S_s(x,y,z)$, $K_{xx}(x,y,z)$);

W – the functions of spatial coordinates and time ($W = W(x,y,z,t)$);

Ω – model area;

$H_0(x,y,z)$ – known head distribution at the initial moment of time;

Γ_1 – border with the given head;

$H(x,y,z,t)$ – head value along the border Γ_1;

Γ_2 – border with the given water flow rate;

K_n – normal-to-border hydraulic conductivity Γ_2;

$Q(x,y,z,t)$ – water flow rate per unit of volume.

The functions $S_s, K_{xx}, K_{yy}, K_{zz}$, W can be the functions of spatial coordinates ($S_s = S_s(x,y,z)$, $K_{xx}(x,y,z)$).

To schematize faults and the pit area, we used the boundary conditions *Barrier* and *Drain,* which belong to the boundary conditions of the second type. The collected input data were preprocessed by using ArcGIS software (ESRI), including faults and boreholes. The model outlines and hydraulic conductivity map were built, and model layers were defined in cross-sections (Fig 3). Each borehole was provided with attributive information including borehole numbers, absolute surface elevation, absolute elevations of cross-section layers, hydraulic conductivity of water-bearing rocks, and absolute elevations of ground water. Based on the above data, the outline of the model area was laid, and hydraulic conductivity and areal recharge maps were built. Figure 3 shows a schematic map of the actual data.

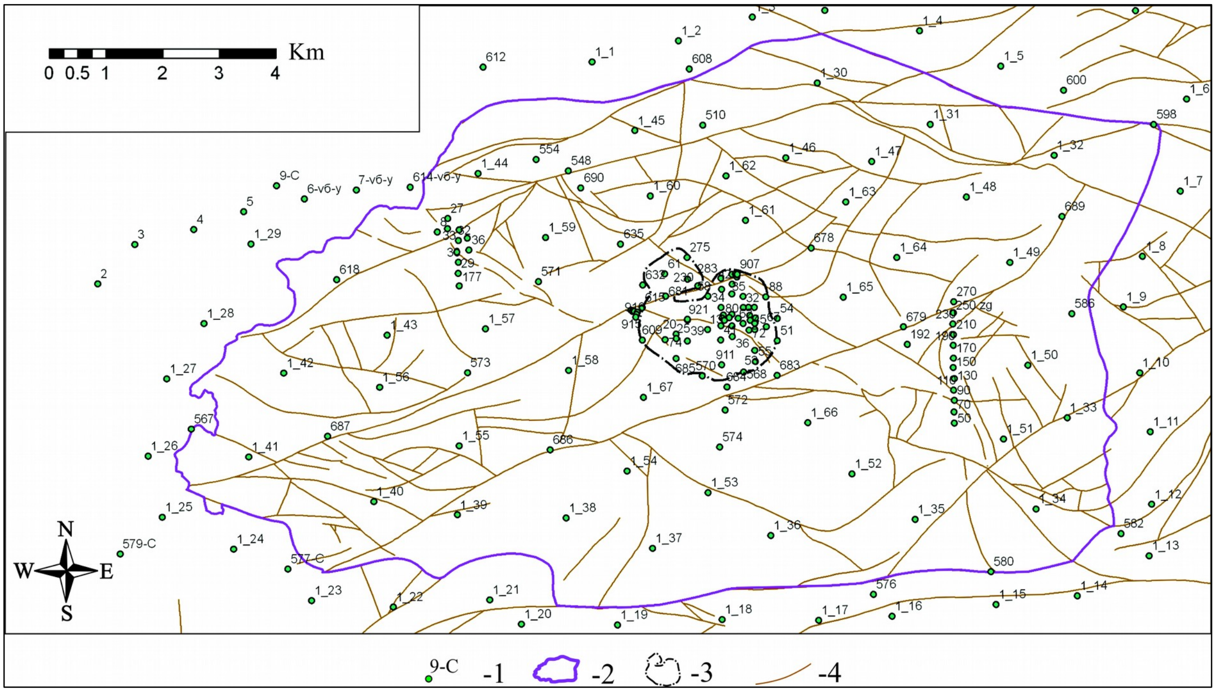

Figure 3. Schematic map: (1) Borehole, figures on top signifies the borehole number and index, (2) Model outline, (3) Open pit outline, (4) Faults

Modeling

The GMS 9.0 software tool was used to process the collected and GIS prepared data of the Aktogay copper deposit mining research area (GMS, 2014). The MODFLOW module of the GMS system was applied to solve the stationary and non-stationary filtration (1 and 2) equations. In the cross-section, the model area is schematized in the form of 4 layers. The pattern interval towards the x axis is 192.515 meters, and towards they axis is 110.774 meters. Absolute elevations of the roof and floor of specified layers were set using the 2DScatterPoints module. The GIS system generated an SQL-request for data sampling based on the roof and floor layer elevations that were preliminarily tied to boreholes and additional points. Additional fields were introduced and tables were generated to use in GMS. The data sets were also interpolated in a 3D pattern preparation. Roof and floor matrices were created for each of the model layers. The hydraulic conductivity of the rocks varies over the area. The first layer's hydraulic conductivity values were tied to boreholes with parameters ranging from 0.001 to 1.085 meters per day. The average hydraulic conductivity is 0.17 meters per day. The second and third layers of hydraulic conductivity were set at 0.016 meters per day (Yerikuly, 2014). The area recharge was specified for the upper model layer and was calculated based on the mean long-term yearly precipitation of 194 mm per year or 0.000532 meters per day. The discharge to the mining deposit groundwater area is 10-30% of the precipitation. The maximum level of precipitation of 290 mm per year is also taken into account as one of the possible scenarios. Bahrami (2014) developed one of the numerical modeling systems by using the SEEP/W finite element model. The model has been used to predict groundwater inflow to open pit mine from a confined aquifer, for designing an effective groundwater management program, for minimizing the mine water adverse effects for mine pit operations.

Model calibration

The model calibration was carried out to check the model compliance with the existing hydrogeological conditions. The calibration procedures involved reverse stationary problem derivation. Since the deposit has not been developed, and the area under study and adjacent territories do not have any factors changing hydrogeological conditions with time, the reverse non-stationary problem was not reviewed. The reverse stationary problem solution was worked on by updating the hydraulic conductivity and areal recharge maps. The undisturbed hydrogeological conditions for 1980 were reproduced in the model. Boundary conditions of the first type were set along the model outline based on a hydro-isobath map built from the actual field data (Figure 4). Boundary conditions of the second type *barrier* were set along the lines of major faults (Figure 4). For the reserve stationary problem solution, the hydraulic conductivity was selected.

The modeling results were compared with the field data, and the actual levels were measured in the boreholes. Hydraulic conductivity data and recharge area values were updated (Yerikuly, 2014). Hydraulic conductivity values obtained during filtration tests were accepted as initial data. The model was run repeatedly until calculated indicators corresponded to the actual levels measured in the boreholes. Figure 4 shows a print screen taken during the GMS system processing. The reverse stationary calculations of the model were correlated to the measured data of the field boreholes. Iso-lines show hydro-isobath lines by using the undisturbed mining field conditions in1980 (Figure 4). Point symbols represent the observation boreholes. The bar chart is on the left side of the borehole symbol (Figure 4). The size of the bar chart is proportional to the modeling error, and its direction shows the character of the error. The green color indicates that the error is less than 2.5 meters, and the yellow color indicates 2.5-5 meters (Figure 4).

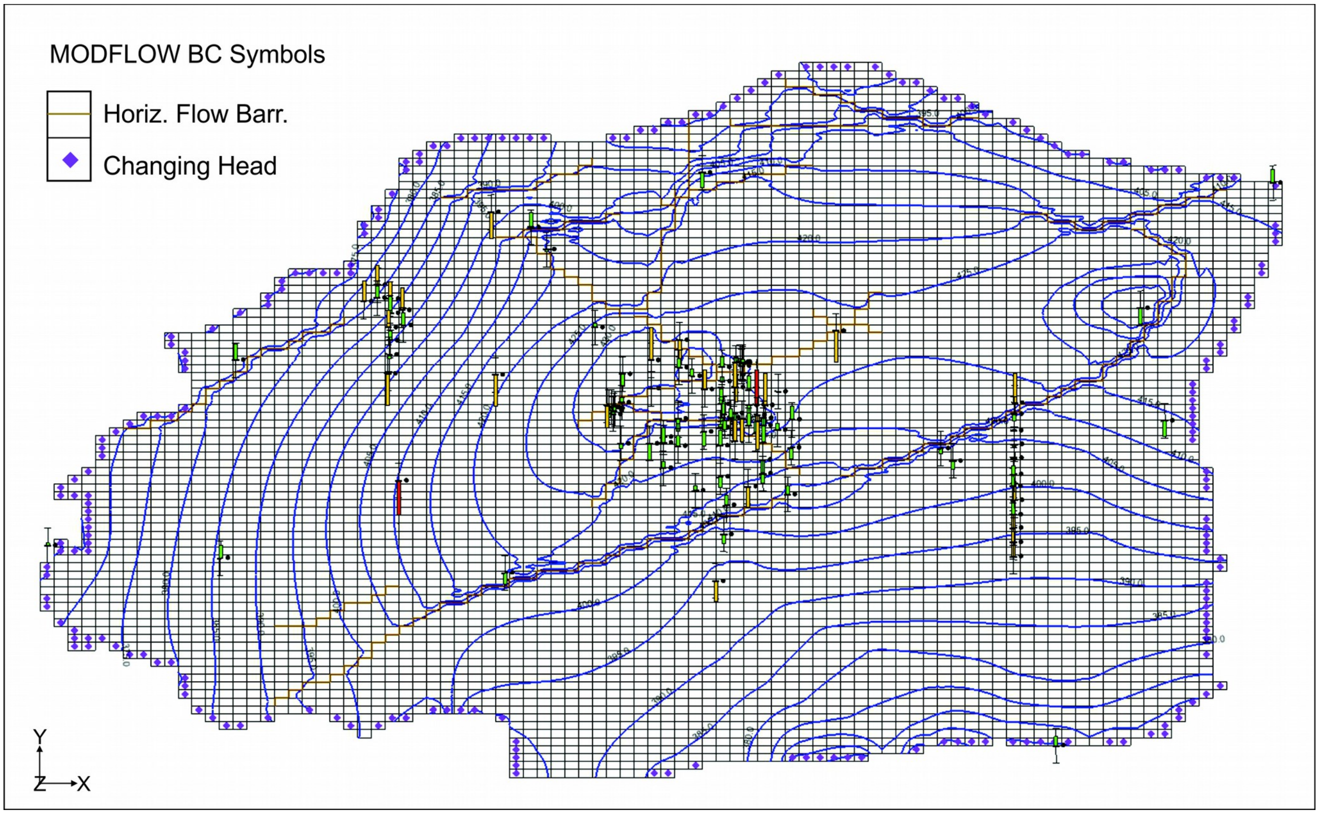

Figure 4. Results of the reverse stationary problem solution on the model in general

The errors in the reverse stationary results were calculated: mean error (*Mean Error*), mean absolute error (*Mean Abs. Error)*, and root mean square error (*Root Mean Sq. Error*) in meters (Table 1).The modeling output results had the acceptable error level for fractured rocks with irregular hydraulic conductivity over the area. The values of hydraulic conductivity and areal recharge, selected according to the results of the stationary problem solution, corresponded to the test data. The accuracy of the reverse stationary problem solution complied with the requirements specified for the model. The model calibration involved the reverse stationary problem solution. The developed conceptual model was represented on a 3D pattern. Thus, matrices of hydraulic conductivity and areal recharge were built, and head and barrier setting blocks were defined. For solution control, the model was provided with a layer containing point objects with preset ground water levels and observation boreholes.

Table 1. Errors of the reverse stationary problem solution

Item	Value
Mean Residual (Head)	-0.1598
Mean Absolute Residual (Head)	1.9819
Root Mean Squared Residual (Head)	2.4991

Model application for the prediction analyses

A modeling of the pit water inflow has been implemented for the period from January 1, 2015 until January 1, 2065. The forecast period is 50 years. It assumed that the mining pit depth would increase by an average of 10 meters per year. Consequently, the first modeling depth of 100 meters would be reached by the end of 2025, and the second design depth of 585 meters would be reached by2065.The mining pit operation was simulated using second type *drain(DRN)*boundary conditions. The model polygons of *drain*-type for each model layer were complemented. The forecast period, from January 1, 2015 to January 1, 2065, was divided into stress periods. The model was not changed during the 50 stress periods, each stress period covering one year. The elastic water yield was set at 0.000001, and the gravity water yield at 0.007. The initial groundwater distribution level for each model layer was set based on the reverse stationary output (Yerikuly, 2014). The *drain*-type schematizing polygons were tied to hydraulic conductivity values and pit bottom elevations. The pit area polygon is about 5 square kilometers, which makes 255 vertical blocks. When the conceptual model was displayed, matrices of hydraulic conductivity, elastic and gravity water yield, and area recharge were developed. The head and boundary condition blocks for the second type barrier and drain were specified. The groundwater levels were calculated for the forecast period. Modeling results for the pit depths of 100 and 585 meters were presented (Figure 5 and 6). The mining pit depth of 100 meters was estimated to be reached by the end of 2025, and the 585 meter-depth was expected by the end of 2065, the final forecast period.

RESULTS AND DISCUSSION

We have analyzed and forecasted the water inflow to the quarry with development a hydrogeological modeling methodology. This methodology consisted of several steps, including analysis of the hydrogeological conditions, research area conceptual model preparation, input data collection with transformation of consistent units for geo-information technology processing, modeling, calibration and model verification of natural physical conditions. A calibrated model was used for the quarry water inflow prediction in the copper deposit operation over the next 50 years; from 2015 to2065.The mining pit water inflow was calculated based on the water balance. The groundwater component was defined

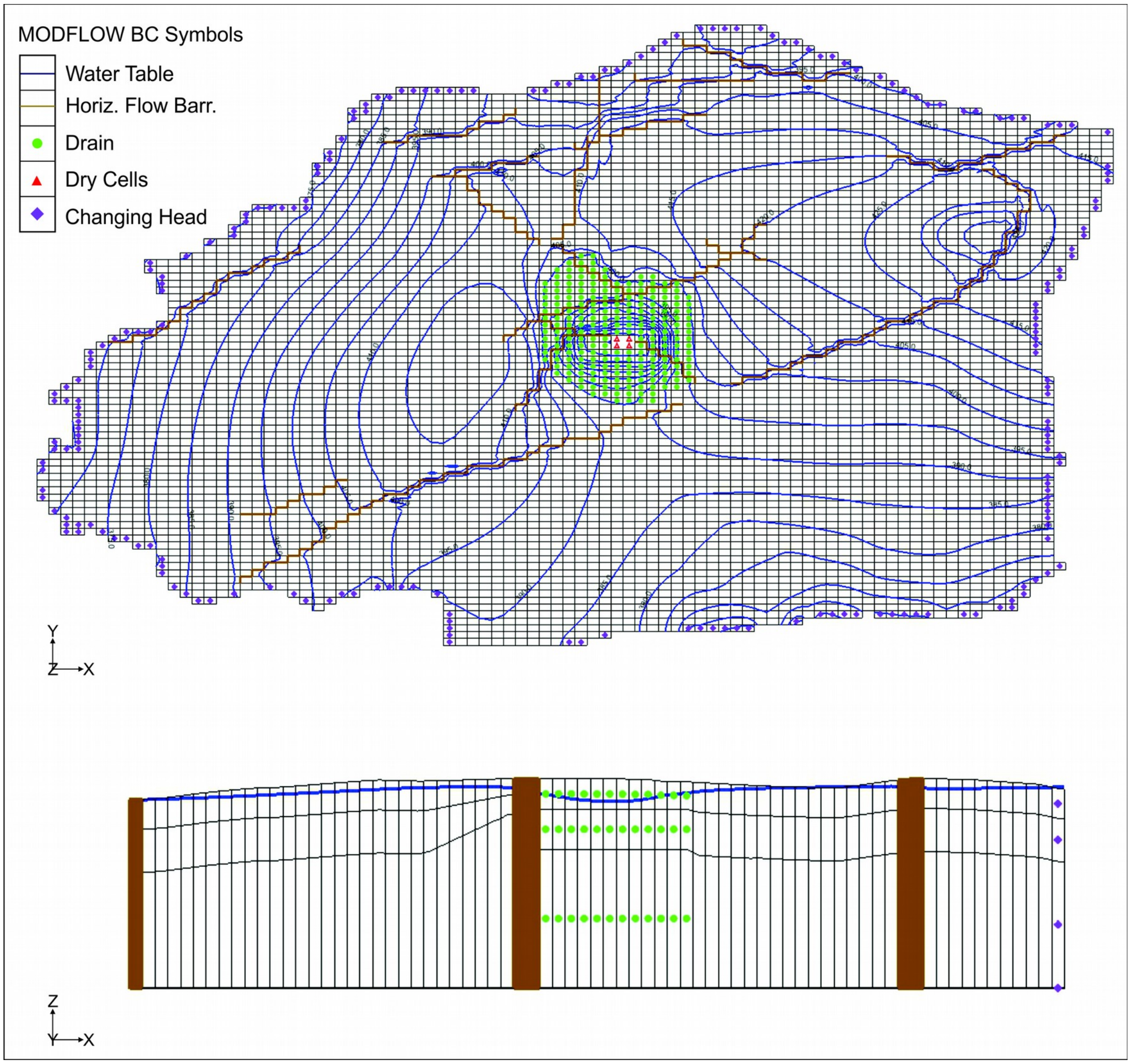

Figure 5. Hydro-isobaths of 2025 year modeling result with the reference level cross section.

during predictive periods. Groundwater inflow scenarios to the mining pit are shown in Figure 7. The groundwater inflow is computed as 2551.6 m^3/day or 106.3 m^3/hour for a mining pit depth of 100 meters. For the mining pit depth of 585 meters the groundwater inflows are 6447.3 m^3/day or 268.6 m^3/day. The modeling output complies with the results of the water balance (Figure 8) (table 2) (Yerikuly 2014).

CONCLUSION

As stated earlier, we have modeled and predicted the water volume changes for one of Kazakhstan's mining operations until 2065. Our analysis and modeling provides forecast data for the design of the water drainage system. Mining exploration is expensive and environmentally complicated. Water movement, including water volume changes, is an important research task for the proper development of any mining exploration. The maximum groundwater inflow to the mining pit is computed in 270 cubic meters per hour. We achieved our goal to predict the water volume changes within the mining operation for the next 50 years, until the year 2065. Several mining development scenarios with groundwater volume changes were prepared. One of the modeling scenarios was related to the mining pit exploration up to a depth of 100 meters. The groundwater inflow was computed at 106.3 m^3/hour, or

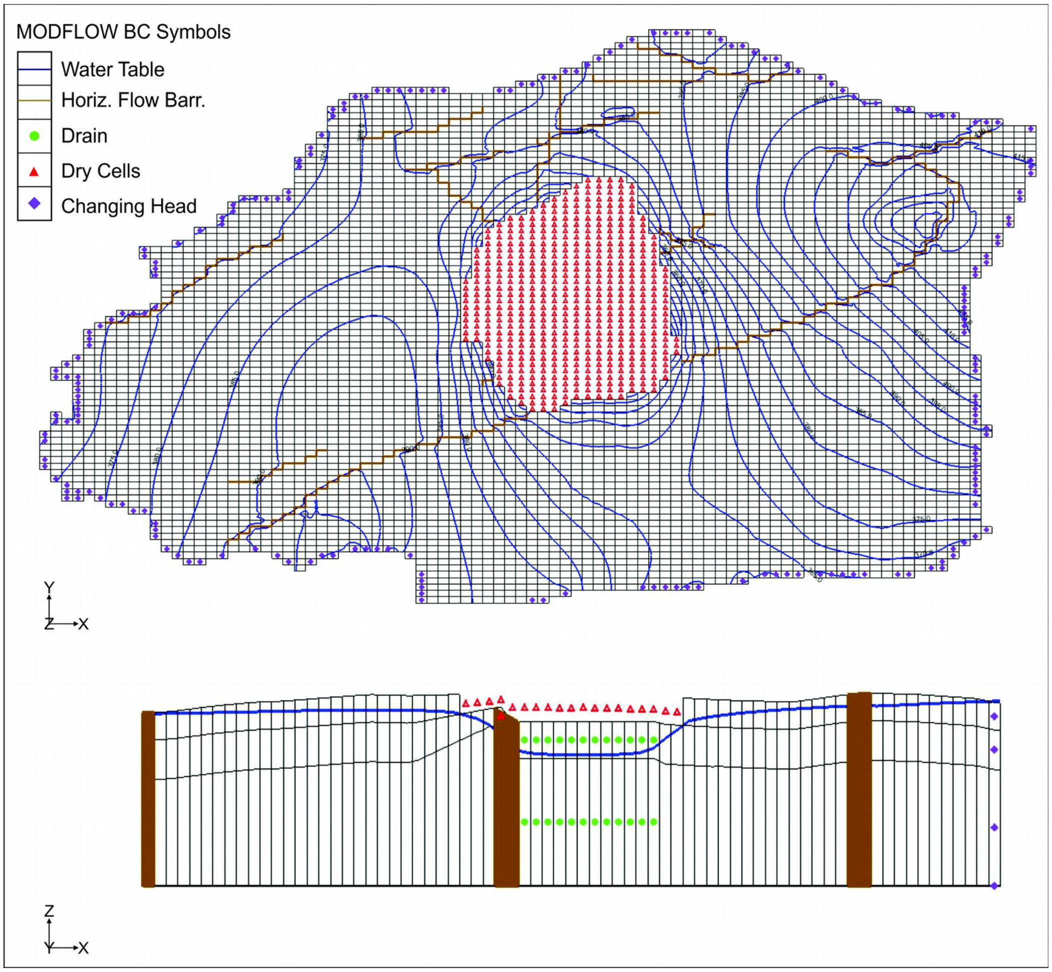

Figure 6. Hydro-isobaths of 2065 year modeling result with the reference level cross section.

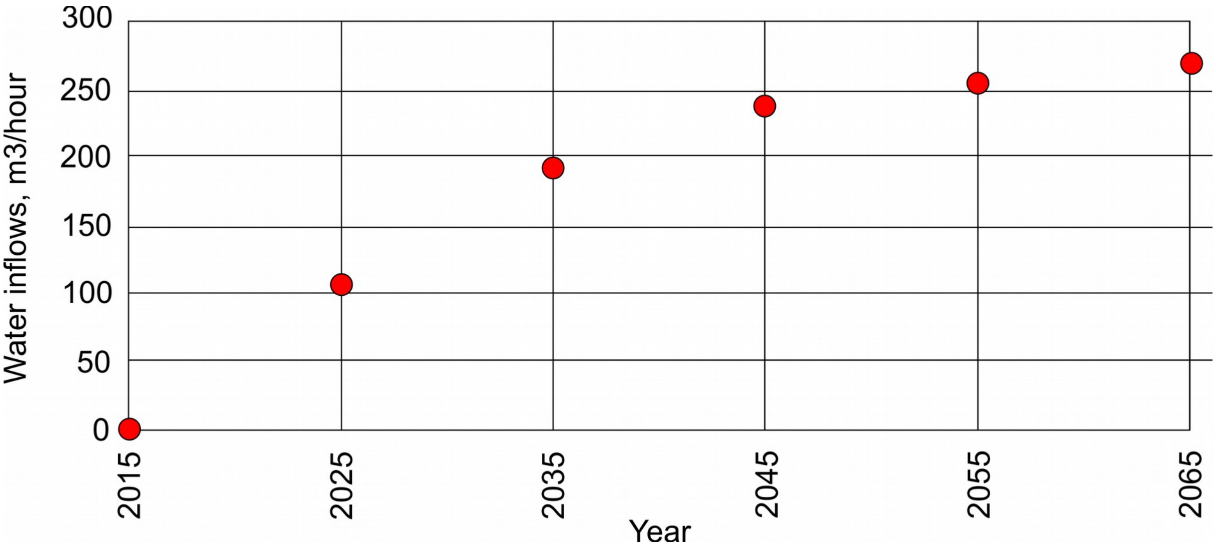

Figure 7.Variation of groundwater inflows to the pit

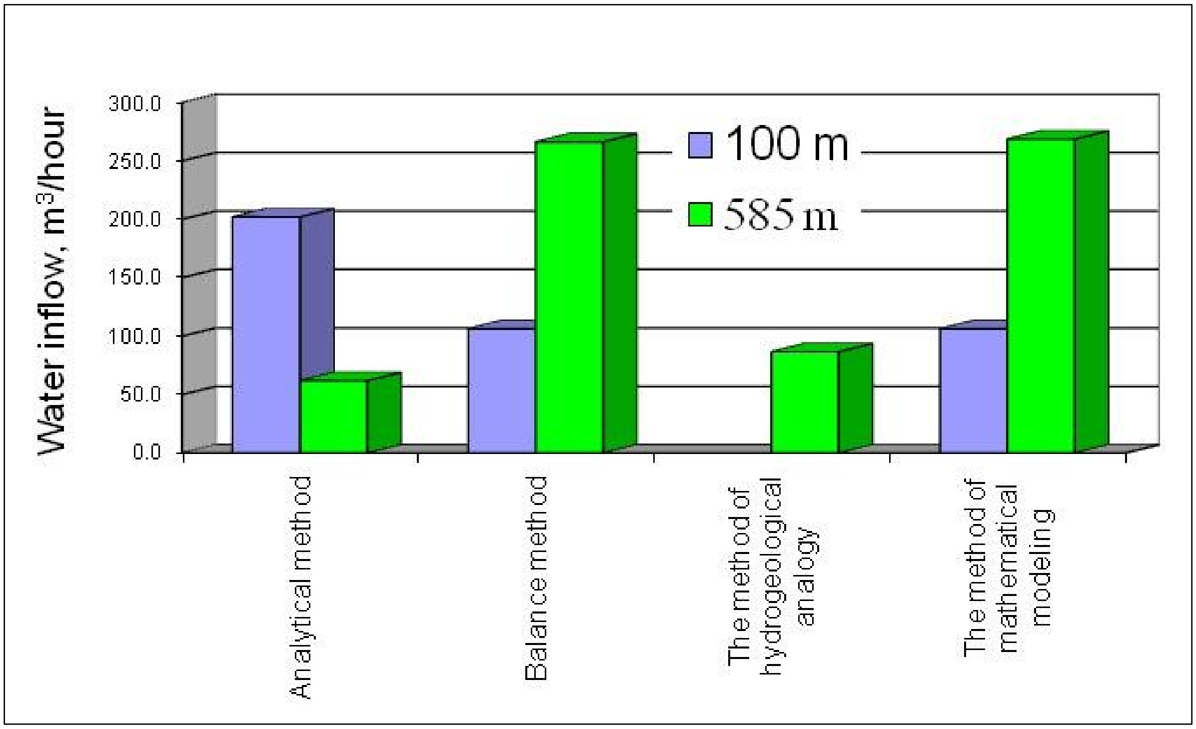

Figure 8. Comparisons of water inflow by mathematical modeling method and earlier methods for the mining pit depths of 100 and 585 meters

2551.6 m^3/day for this scenario. Another modeling scenario for the same mining pit had a depth at 585 meters. The groundwater inflow for this scenario was computed at 268.6 m^3/hour, or 6447.3 m^3/day. Surface run-off can be eliminated by a network of drain trenches arranged around the open mining pit. A groundwater run-off can be drained at the pit entries. A pit water tank for water treatment is necessary in the mining operation (Czop 2010, Golestanifar and Ahangari, 2012, Jiang 2012) to design the dewatering well pumping rates (Jiang, 2012). We are planning to use an integrated DHI MIKE SHE surface and groundwater modeling software as well as data from Kazakh National Space Company's KazEOSat-1 satellite, which provides one-meter high resolution images, to advance this research.

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