Modelling Groundwater Inflow to a Mine Pit: A Monte Carlo Approach

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Abstract Development of hydrological modelling methods to describe the behaviour of groundwater and surface runoff has been the subject of research for many years. This study aims to develop a Monte Carlo approach for simulating the probable formation of a mine pit lake in Kışladağ, Turkey by modelling the groundwater inflow to the open pit together with the precipitation, surface runoff and evaporation. Modelling methodology is based on a systems modelling approach. Results reveal the validity of the proposed system dynamics model for estimation of groundwater inflow to the mine pit. Sensitivity analysis are also carried out to assess the influence of model parameters on groundwater inflow. The results indicate that the model is more sensitive to the changes in radius of influence than hydraulic conductivity and static water level.

Keywords: Hydrological modelling, Mine Pit, Groundwater, System dynamics modelling

1. Introduction

Mining, which generally requires deep excavations that are completed below the static groundwater level, may impose a significant environmental impact on groundwater resources. Groundwater flow into the pit, together with the direct precipitation and surface runoff, contributes to the formation of a pit lake (Castendyk and Eary 2009). The unexpected inflows in large quantities may cause undesirable effects including project delay and many safety and environmental problems (Bahrami *et al*. 2016).

In literature, several numerical models have been developed to estimate groundwater inflow to open mine pits and to predict the hydraulic head in observation wells at different distances from the pits (Crowe *et al*. 2004; Hernández *et al*. 2012; Singh *et al*. 2012; Bahrami *et al*. 2014; Bahrami *et al*. 2016). For example, Crowe *et al*. (2004) developed a numerical model to predict transient hydraulic head considering infiltration, evapotranspiration and surface water flow together with the water and contaminant fluxes across the aquifer–wetland interface. Singh *et al*. (2012) used a SEEP/W finite element model to predict groundwater inflow to the open pit in Sindh, Pakistan. The authors carried out sensitivity analysis to determine the parameters affecting groundwater inflow and found that the model is very sensitive to permeability of the aquifer. Bahrami *et al*. (2016) applied the artificial neural network (ANN) coupled with genetic algorithm (GA) and simulated annealing (SA) to predict groundwater inflow to an advancing open pit mine and the hydraulic head in observation wells at different distances from the center of the pit during its advance.

The aim of the present study is to develop a Monte Carlo simulation for the prediction of groundwater inflow to the Kışladağ Mine Pit in Turkey. For this purpose, system dynamic modelling approach is developed using GoldSim by taking into consideration the effects of direct precipitation, surface runoff and direct evaporation.

2. Materials and Methods

2.1. Study Area

The Kışladağ Gold Mine has been in operation since 2006, and is projected to end by 2030, leaving a large open pit. Main facilities of the mine consist of a leach pad, a waste rock storage area, and an open pit, with the planned expansion of the leach pad in the north and waste rock storage area in the south of the mine site. The terrain in the vicinity of the mine site is rolling hills from approximately 950 m in the leach pad area to 1300 m to the top of the Kışladağ Mountain.

In the region, monthly temperatures vary between 25.2^{0}C (August) to 2.23^{0}C (January). Long term annual evaporation for Kışladağ is around 1198 mm. The average annual precipitation is calculated as 493 mm for the mine site using long-term (1975-2012) precipitation data series (Yazicigil *et al*. 2011; Yazicigil *et al*. 2013). The average annual precipitation for Kışladağ is noted as 491 mm between the years 2001 and 2012. The study area is illustrated in Figure 1.

2.2. Model Development

The probable formation of a mine pit lake in Kışladağ is simulated by undertaking a stochastic approach, using Monte Carlo analysis. Groundwater inflow to the mine pit is simulated based on the effects main environmental variables, such as precipitation, surface runoff and evaporation. GoldSim Academic version (GoldSim Technology Group 2017) is used as the modelling environment. The mass balance equation used to calculate the volumetric balance of the pit lake is given below:

$$\Delta\, Storage = (Direct\ Precipitation) + (Runoff) + (Groundwater\ Inflow) - (Direct\ Evaporation) \quad (1)$$

$$\frac{dS}{dt} = \frac{(P+Q_r)\times A}{1000} + Q_g - \frac{E\times A}{1000} \quad (2)$$

where S is storage (m^3), P is precipitation ($mm\ s^{-1}$), Q_r is runoff rate ($m\ s^{-1}$), Q_g is groundwater inflow ($m^3\ s^{-1}$), E is evaporation rate ($mm\ s^{-1}$), and A is area (m^2).

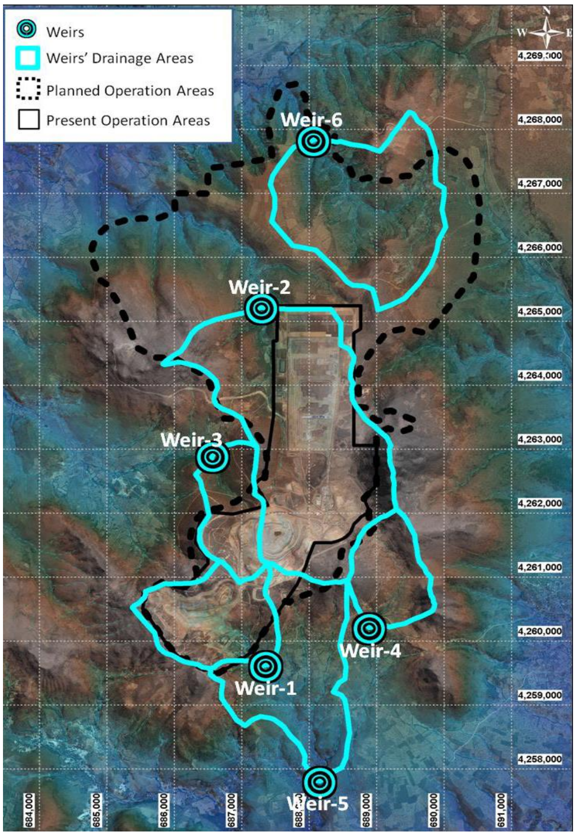

Figure 1. Study area

To evaluate the direct precipitation into the mine pit, the percentage of the pit area (785398 m^2) inside the drainage area is determined. Precipitation values are assigned as stochastic input data with triangular distribution in three class (0%, most likely and 100%). For this purpose, the wettest and driest years are determined, and the average annual precipitation is calculated using time-series precipitation data between the years 1975 and 2012 (Yazicigil *et al*. 2011; Yazicigil *et al*. 2013). Study area is subject to net evaporative losses due to its semi-arid nature, thus the temperature values of meteorological records are entered to the model as time series data. Evaporation is calculated by Turc method, which is given in below equations (Turc 1961):

$$E = \frac{P}{\left[0.9+\left(\frac{P}{I_T}\right)^2\right]^{1/2}} \quad (3)$$

$$I_T = 300 + 25T + 0.53T^3 \quad (4)$$

where T is the mean annual temperature (^{o}C).

Runoff rate is estimated using USDA Soil Conservation Service's runoff curve number (*CN*) method (USDA, 1986), and are represented by equations (5) and (6).

$$Q_r = \frac{(P-0.2s)^2}{(P+0.8s)}$$

(5)

$$s = \frac{1000}{CN} - 10$$

(6)

where s is potential maximum soil moisture after runoff begins (mm). Considering the hydrologic soil groups of the study area, *CN* value is assigned as stochastic input data range between 77.1 and 100 (USDA, 1986).

Regional groundwater inflow to the open pit is estimated using Dupuit - Forchheimer equation for radial flow conditions for an unconfined well, ignoring the vertical flow (equation (7)). For this purpose, during the development of conceptual model related with the groundwater inflow, the mine pit is assumed as a cylinder, radius of which is effectively equivalent to its irregular size and shape. Groundwater inflow is estimated using the equation below:

$$Q_g = \frac{\pi\cdot K\cdot({h_0}^2-{h_w}^2)}{\ln\frac{r_0}{r_w}} \quad (7)$$

where K is hydraulic conductivity ($m\ s^{-1}$), h_0 is pre-mining groundwater level (m), h_w is the depth of the pit (m), r_w is the pit diameter (m), and r_0 is radius of influence (m). Here, K, h_0, and r_0 are assigned as stochastic input data, while r_w is assumed as a constant input. Since operational season, from September 2012 to April 2015, is modelled, varying h_w values are entered to the model as time series data.

3. Results and Discussion

The model is run twice for (i) probabilistic version with stochastic inputs and (ii) deterministic version with fixed values, which are selected from the ranges for each parameter. The comparison of stochastic and deterministic model is given in Table 1.

According to the deterministic model results given in Table 1, groundwater inflow to the mine pit is zero, which is not reliable, since the lumped value of K is assigned for an area with highly heterogeneous permeability. The results also reveal that there is no difference between a range and fixed value of evaporation, which underpins that evaporation rates are not dependent on recharge as expressed by the Turc method and the temperatures between September 2012 and April 2015 do not vary much to result in dramatic evaporation rates.

The output of stochastic model developed in GoldSim with 100 realizations for groundwater inflow is given in Figure 2. The change of mine pit storage with time is also given together with groundwater inflow for distribution classes in Figure 3. According to the simulation results, the relationship between groundwater inflow and storage simulates well, and both follow an increasing trend during the operational period from September 2012 to April 2015.

In inverse technique and also for trial and error technique, sensitivity analysis plays a key role in the calibration process by identifying those parameters that are most important to model reliability. GoldSim has a sensitivity analysis algorithm embedded in the program. Parameter sensitivity analysis are carried for *CN*, h_0, K, r_0 and precipitation. The results illustrated in Figure 4 reveal that

Table 1. Comparison of stochastic and deterministic models

	Stochastic model (100 realizations)	Deterministic model (1 realization)	Unit
GW inflow	0.005362	0	
Precipitation	0.0005333	0.0004282	
Evaporation	0.0005622	0.0005622	$m^3\ s^{-1}$
Runoff	3.967	2.233	
Storage	3.973	2.203	

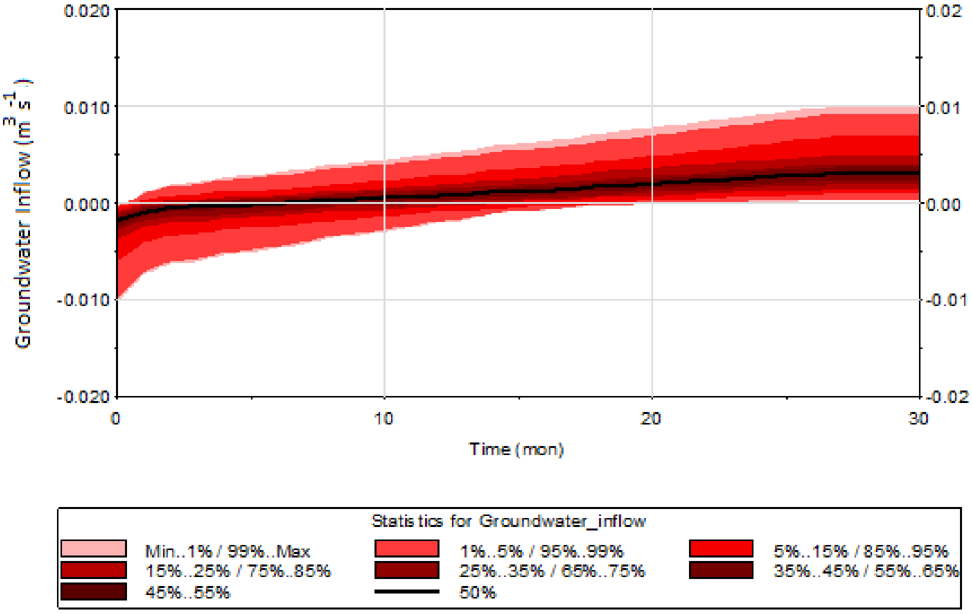

Figure 2. Stochastic model output for groundwater inflow

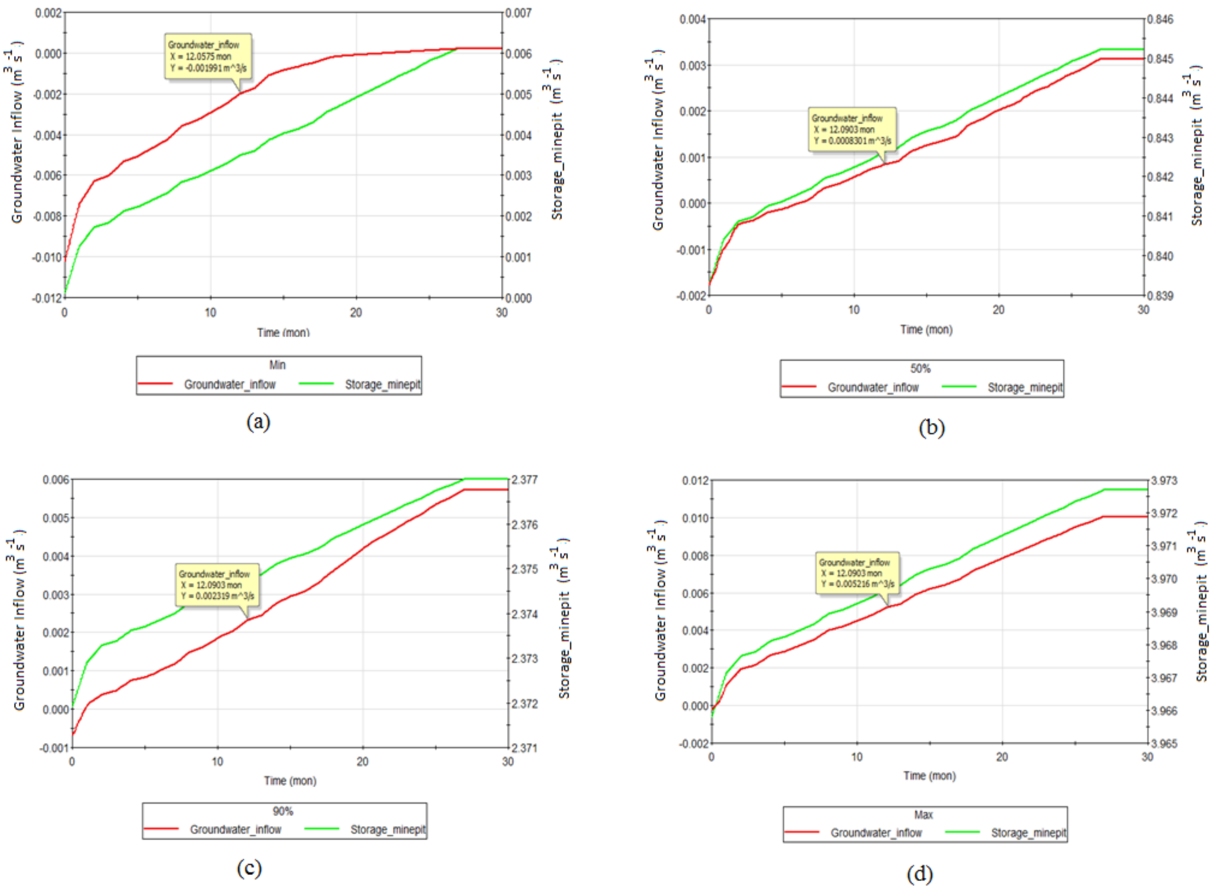

Figure 3. Model outputs for groundwater inflow and storage for different distribution classes: (a) min (b) 50% (c) 90% (d) max

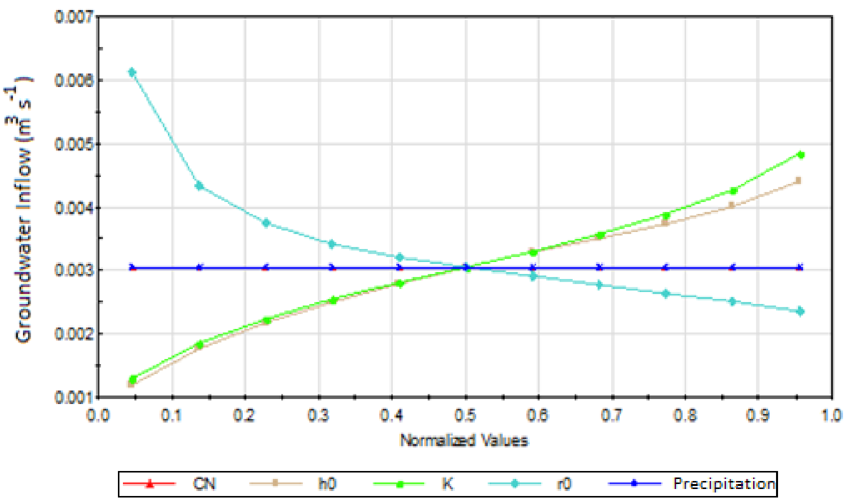

Figure 4. Parameter sensitivity analysis results

model is highly sensitive to the changes in r_0, K and h_0. The variation in precipitation and *CN* for runoff rate do not change the model outcomes.

4. Conclusions

The present study aims to develop a system dynamics model with a Monte Carlo approach to simulate the groundwater inflow to the Kışladağ Mine Pit together with precipitation, surface runoff, and evaporation.

The model outcomes reveal that groundwater inflow follows an increasing trend during the operational period from September 2012 to April 2015, and it has a significant impact on the change of storage values, thereby probable formation of mine pit lake in Kışladağ. Results reveal the validity of the proposed system dynamics modelling approach for estimation of groundwater inflow to the mine pit, and simulation of the change in storage capacity in time.

Parameter sensitivity analysis are carried for *CN*, h_0, *K*, r_0 and precipitation to assess the most significant parameters affecting model outcomes. According to the results, the model is highly sensitive to the changes in r_0, *K* and h_0, whereas the variation in precipitation and *CN* for runoff rate do not have an influence on the model response.

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