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PROBABILISTIC RISK ASSESSMENT OF ACID MINE DRAINAGE GENERATION RESULTED FROM CHALCOPYRITE OXIDATION PROCESS WITHIN SARCHESHMEH COPPER MINE TAILINGS

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Abstract: A probabilistic predictive method for estimating the risk of acid mine drainage generation within the copper tailings dump of the Sarcheshmeh copper mine, Iran, has been presented in this paper. For this purpose, the input and output parameters were determined after gathering historical data and building an appropriate database. Some of the critical parameters, including depth, and concentrations of bicarbonate, chloride, nitrate, and nitric, were considered input data, while the output parameters were chalcopyrite, pH. The best distribution functions on each input parameter were found by Chi Sq. criteria. Subsequently, the best linear statistical relationships between the input and output data were determined. Then, the best probability distribution functions of output parameters were defined by inserting the input parameters in the obtained linear statistical relationship. The results showed that the remaining chalcopyrite fraction values were between 0.1094 % and 0.2159% at a 90% probability level. In contrast, the pH values would be expected between 3.13 and 8.04 at this probability level.

BACKGROUND

Acid mine drainage (AMD) is one of the environmental issues which generally results from mining activities. AMD is naturally generated when the sulfide minerals are exposed to atmospheric weathering. AMD can affect the environment long-term if there is no appropriate environmental management. The most important chemical reaction of chalcopyrite oxidation in AMD generation is as follow:

$$CuFeS_2 + 16Fe^{3+} + 8H_2O \rightarrow Cu^{2+} + 17Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad (1)$$

As seen, the complete oxidation of chalcopyrite produces no acid product. Nevertheless, a combination of the ferrous iron and iron hydroxyl oxidation process is known to regenerate the acid (Reaction (2)).

$$2CuFeS_2 + \frac{17}{2}O_2 + 5H_2O \rightarrow 2Cu^{2+} + 2Fe(OH)_3 + 2SO_4{}^{2-} + 4H^+ \quad (2)$$

Rimsdith et al. (1994) found that chalcopyrite oxidation accelerates with rising the ferric iron concentration. Over fifty years, significant research has been done to study the pyrite oxidation process resulting from mining wastes or tailing. For instance, Doulati Ardejani et al. (2004) proposed a finite volume model solution to simulate the pyrite oxidation process in coal tailings. Their suggested model was based on oxygen diffusion, groundwater flow, and transportation of oxidation products. Doulati Ardejani et al. (2008) presented a one-dimensional mathematical model incorporating the finite volume technique to describe pyrite oxidation and transportation of the oxidation products from a coal waste dump (Doulati Ardejani et al., 2008). Jodeiri Shokri et al. (2016) presented a two-dimensional numerical finite volume model developed to describe the long-term pyrite oxidation and subsequent products transportation from an abandoned coal waste pile in Iran. Hadadi et al. (2019) applied a probabilistic approach to predict how acid mine drainage is generated within coal waste particles in the Anjir Tangeh coal washing region. Also, the pyrite oxidation process was assessed by this probabilistic method throughout the coal tailings resulting from the Alborz-Sharghi coal processing plant (Hadadi et al., 2020). Jodeiri Shokri et al. (2020) applied gene expression programming (GEP) for predicting the AMD generation potential throughout copper tailings. Four predictive relationships for the remaining pyrite

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fraction, remaining chalcopyrite fraction, sulfate concentration, and pH have been suggested by applying GEP algorithms. Although many research works have been conducted on AMD generation based on the pyrite oxidation process, there is a bit of significant research on predicting the chalcopyrite oxidation process. Therefore, this paper predicted chalcopyrite oxidation within a copper waste pile using a probabilistic method.

MATERIALS AND METHODS

Site description

Sarcheshmeh copper mine is situated 50 km to the south of Rafsanjan in the central part of Zagros Mountain Range. Based on the field observations and previous research works, mineral processing operations result in more than 24 megatons of tailing over an area of more than 4 km2 within the studied area. In some cases, the dump height reaches 12 m (Jannesar Malakooti et al., 2014).

Methodology

All experimental data were collected from previous studies such as Jodeiri Shokri et al. (2020) (**Table 1**). The depth of the wastes within the pile, the fraction of diffused oxygen through the wastes particles, chloride, nitrate, and nitric and bicarbonate concentration within the pile as capability of AMD neutralization were considered inputs data. Moreover, the remaining chalcopyrite fraction and pH were chosen as outputs data. Then, comprehensive statistical analyses were done to find the best relationships between outputs and inputs.

Table 1: Database of Sarcheshmeh copper tailings dump (Jodeiri Shokri et al. (2020))

No.	Depth of the tailings (m)	Bicarbonate (mg/lit)	Chloride (mg/lit)	Nitrite (mg/lit)	Nitrate (mg/lit)	Remaining chalcopyrite fraction (%)	pH value
1	0.3	0	42.4	19.8	4.3	0.06	2.9
2	0.6	0	40.7	11	3.2	0.086	3.1
3	0.9	0	34.1	12.2	1.8	0.112	4.5
4	1.2	0	30.7	10.2	3.1	0.129	4.7
5	1.5	20	19	14.9	3.9	0.133	5.6
6	1.8	25	22.4	16.9	4.3	0.134	6.7
7	2.1	30	19	14.3	5.2	0.134	7
8	2.4	25	17.1	14.7	5.5	0.135	7.8
9	2.7	30	17.2	20.3	7.2	0.135	7.3
10	3	22	15.5	10.6	7.6	0.13	7.6
11	3.3	28	15.5	6.9	6.5	0.136	7.8
12	3.6	26	12.1	6.7	6.3	0.131	8.2
13	3.9	25	13.8	6.3	5.9	0.137	7.9
…	…	…	…	…	…	…	…
57	0.3	52.5	80.82	0.075	7.13	0.049	4.2
58	0.6	0	78.72	0.15	0	0.069	3.8
59	0.9	0	78.78	0.075	0	0.085	3
60	1.2	42	73.99	0.075	0	0.12	6.2
61	1.5	52.5	67.82	0.075	0	0.14	7.4
62	1.8	42	28.61	0.075	0	0.163	8.1
63	2.1	42	25.76	0.05	0	0.177	8.6
64	2.4	47.2	22.61	0.075	0	0.185	8.4
65	2.7	42	18.09	0.075	0	0.186	8.4
66	3	52.5	18.09	0.15	0	0.192	8.3
67	3.3	47.2	18.09	0.075	0	0.2	8.3
68	3.6	46.2	18.09	0.075	0	0.204	7.9
69	3.9	52.5	18.09	0.075	0	0.208	8.1
70	4.2	52.5	22.61	0.1	0	0.208	8

All parameters involved in the chalcopyrite oxidation process are uncertain. Therefore, it is necessary to describe their nature uncertainties based on probability distribution. A probability distribution is a method for presenting the quantified risk for each parameter. @RISK uses probability distributions to describe uncertain values in your Excel worksheets and to show results. There are many forms and types of probability distributions, such as Chi-Sq. Kolmogorov-Smirnov Statistic and Anderson-Darling Statistic. Each of these forms describes a range of possible values and their likelihood of occurrence (@RISK Manual, 2015).

After finding the best probability distribution functions for each of the parameters with @RISK ver.7., the sampling from the functions was done by Monte Carlo simulation in a random. Indeed, Monte Carlo simulation performs risk analysis by building models of possible results by substituting a range of values, probability distribution, for any factor with inherent uncertainty. It then calculates results repeatedly, each time using a different set of random values from the probability functions. Depending upon the number of uncertainties and the ranges specified for them, a Monte Carlo simulation could involve thousands or tens of thousands of recalculations before it is complete. Monte Carlo simulation produces distributions of possible outcome values (@RISK Manual, 2015). Finally, the risk analyses would be finished by finding the probability distributions functions of the outputs.

RESULTS AND DISCUSSIONS

Probability distributions functions

Probability distributions functions were defined applying @RISK ver.7 for each input. According to Chi-Squared Statistics, the best fittings of the distributions for each input were obtained (**Figure 1**).

STATISTICAL ANALYSES

Relationships between each output and all inputs

To estimate the remaining chalcopyrite, finding the best relationship between each output and all inputs is necessary. For this, comprehensive statistical analyses were done using SPSS ver. 20. The best linear regressions between the remaining chalcopyrite fraction, pH values and all inputs are as follow (Eqs. 3 and 4):

$$CPy = 0.017\,B + 0.001\,C - 3.459\times10\text{-}5D + 0.004\,E - 0.008\,F + 0.106 \qquad (3)$$

$$pH = -\,0.293\,B - 0.039\,C + 0.051\,D + 0.019E - 0.150F + 6.913 \qquad (4)$$

Where:

B: Pile depth (m);

C: Bicarbonate concentration (mg/lit);

D: Chloroide (mg/lit);

E: Nitrate (mg/lit);

F: Nitric (mg/lit).

This experimental expression yields value of 0.98 for the statistical parameters of R-square adjusted (**Table 2**).

In the next step, each input's best probability distribution function should be inserted in equations (3) and (4) to estimate the remaining chalcopyrite fraction and pH. The probabilistic prediction was simulated based on the Monte Carlo method. The results of meaningful occurrence probability of predicting remaining chalcopyrite fraction and pH were given in **Table 3**.

The histogram and the graph of the cumulative probability of the results for the remaining chalcopyrite fraction are depicted in **Figure 2**. The results revealed that the values of the remaining chalcopyrite fraction are between 0.1094% and 0.2159% at a probability level of 90%. Also, the remaining chalcopyrite fraction will be lower than 0.1160 and 0.240 at the 5% and 99% probability levels, respectively. **Figure 3** shows the best probability distribution function of the output of the Monte Carlo simulation.

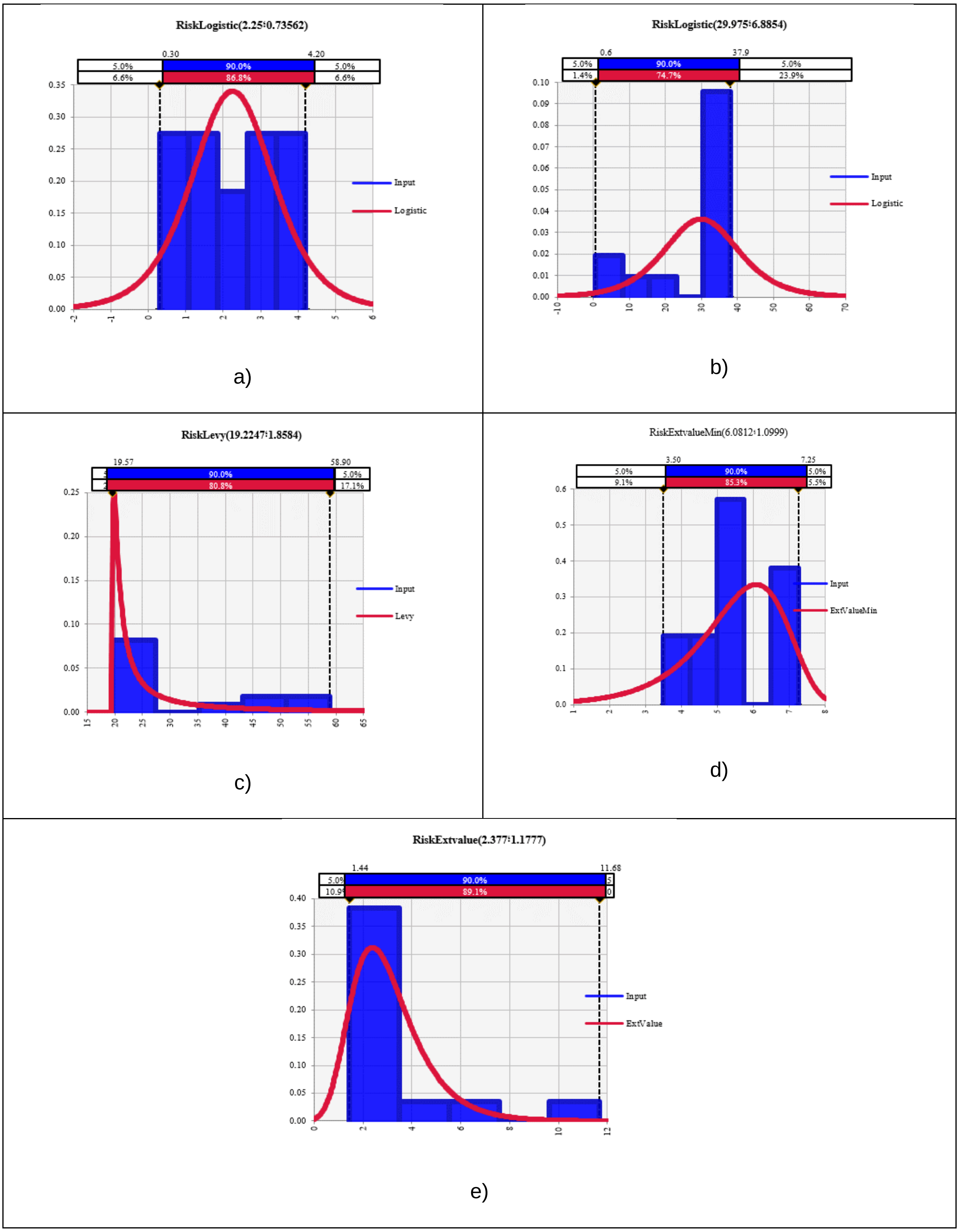

Figure 1: Best probability distribution functions of input parameters; a) depth, b) bicarbonate concentration; c) chloride concentration; d) nitrite, and e) nitrate

Table 2: The statistical results of the linear regression between the remaining chalcopyrite fraction and input data

Statistical parameters	the remaining chalcopyrite fraction (%)	pH values
Mean	0.157	6.73
Median	0.158	7.60
Mode	0.200	7.80
Minimum	0.261	8.60
Maximum	0.009	2.90

Table 3: The meaningful occurrence probability of predicting remaining chalcopyrite fraction

Meaningful occurrence probability (%)	the remaining chalcopyrite fraction after simulation (%)	pH values after simulation
5	0.1160	3.13
50	0.170	4.05
90	0.222	8.04
99	0.240	8.90

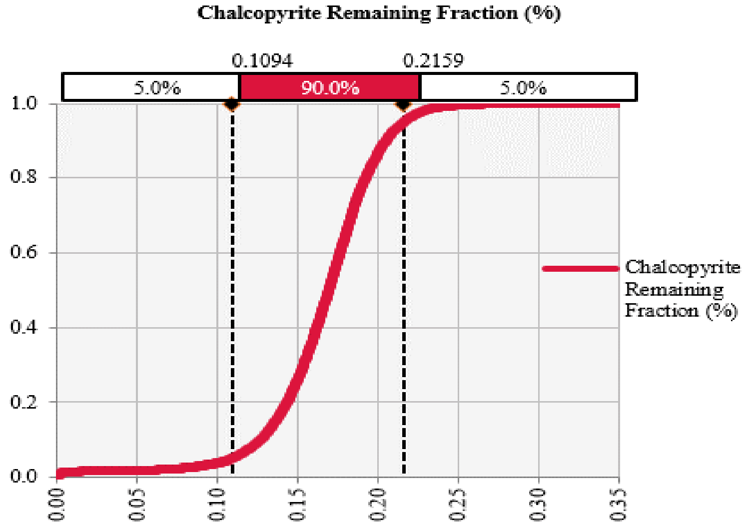

Figure 2: Cumulative graph probability of predicting the remaining chalcopyrite fraction.

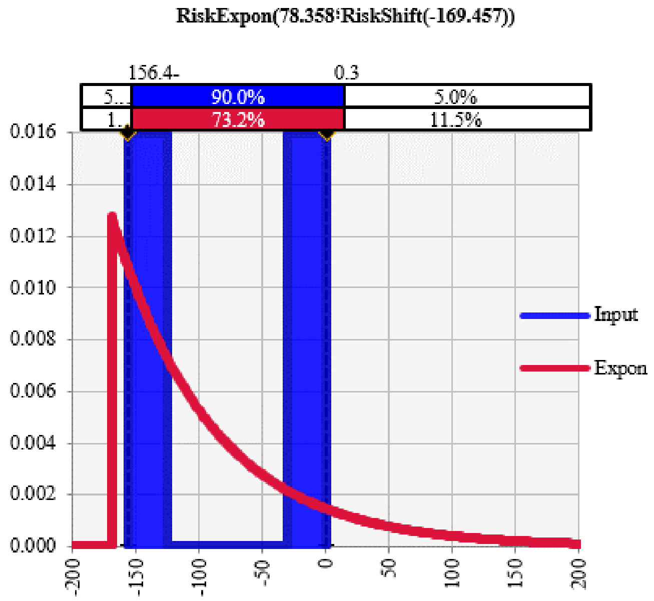

Figure 3: The best probability distribution function of the chalcopyrite remaining pyrite fraction.

The cumulative probability of predicting pH is shown in **Figure 4**. The results revealed that the pH values are between 3.13 and 8.04 at a probability level of 90%. **Figure 5** shows the best probability distribution function of the output of the Monte Carlo simulation.

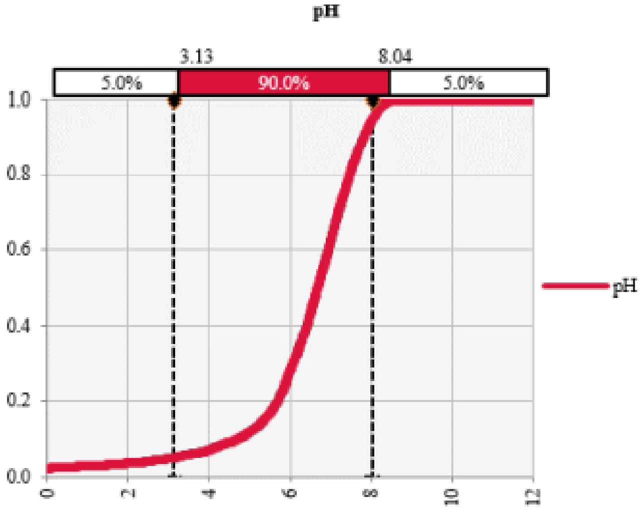

Figure 4: Cumulative graph probability of predicting pH values.

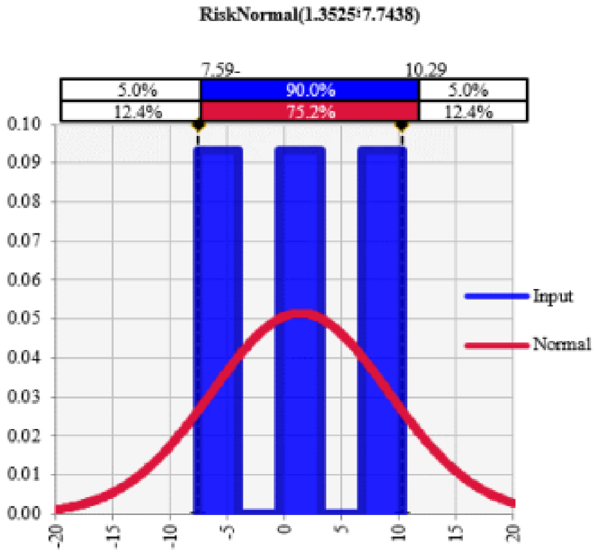

Figure 5: The best probability distribution function of pH values.

CONCLUSIONS

This paper investigated the chalcopyrite oxidation process within the wastes tailings based on the probabilistic method. For this, chalcopyrite remaining fraction and pH were considered as output parameters while bicarbonate concentration, depth of the samples, nitrite, nitrate, and chloride were input data. After building a database, the linear regression method determined the best relationships between output and input data. After finding the best relationships, the probability distributions functions were defined by applying @RISK ver.7 for each input. Then, the distributions were inserted in the statistical relationships to find the probability distributions of pyrite remaining fraction and pH. The results revealed that the remaining chalcopyrite fraction and pH values were lower than 0.894 and 4.6 at a 5% probability level, respectively.

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