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The effect of HCN emissions from tailing storage facilities of a gold mine on public health: findings from a major case study in Thailand

Tác động của HCN phát tán từ hồ chứa nước thải của mỏ vàng đến sức khỏe cộng đồng: Trường hợp nghiên cứu điển hình ở Thái Lan

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Abstract

Cyanide is used to extract gold from gold-bearing ore, resulting in wastewater containing cyanide compounds which is released to a tailing storage facilities (TSF). Hydrogen Cyanide (HCN) is highly volatile and the most toxic form of cyanide. A large gold mine in Phichit Province, Thailand uses cyanide to extract gold from ore, and cyanide contaminated waste product is released into a TSF, which is allowed to have a maximum cyanide concentration of 20 mg/l. There is great concern whether airborne HCN emissions from TSF pose a public health hazard. To assess the effect of HCN emissions from TSF on public health, the AERMOD model was used to simulate the dispersion of HCN from the mine's TSF. The simulated results were compared with acute and chronic inhalation Reference Exposure Levels (RELs) for HCN. The results show that communities living around the mine were likely to be exposed to HCN. At pH 6.9 in the TSF, forty-two communities were likely to be exposed to acute inhalation RELs of HCN, and 2 communities exposed to chronic effect. The simulation showed that the recommended cyanide levels to prevent public health harm should be 2.73 mg/l, not 20 mg/l as permitted by the environmental and health impact assessment (EIA) of the mine.

Keywords: AERMOD; hydrogen cyanide; gold mining; simulation; tailing storage facility.

Tóm tắt

Cyanide thường được sử dụng để trích chiết vàng từ quặng. Sau đó, nước thải có chứa các hợp chất cyanide được thải vào hồ chứa nước thải (HCNT). Hydro xyanua (HCN) là chất bay hơi và có độ độc tính cao nhất trong số các chất cyanide được thải vào HCNT. Mỏ vàng lớn nhất Thái Lan nằm ở tỉnh Phichit sử dụng cyanide để trích chiết vàng. Nước thải có chứa cyanide từ mỏ vàng này được thải ra HCNT với nồng độ tối đa cho phép là 20 mg/l. Đã có những lo ngại về việc số liệu HCN từ HCNT phát tán vào không khí có gây nguy hiểm cho sức khỏe cộng đồng hay không. Để đánh giá tác động của HCN phát tán từ HCNT đến sức khỏe cộng đồng, nghiên cứu này áp dụng mô hình AERMOD để mô phỏng sự phát tán của HCN từ HCNT của mỏ vàng ở tỉnh Phichit. Các kết quả mô phỏng được so sánh với các mức phơi nhiễm tham chiếu cấp tính và mãn tính (REL) đối với HCN. Kết quả nghiên cứu chỉ ra rằng, có 42 cộng đồng phơi nhiễm cấp tính, và 2 cộng đồng phơi nhiễm mãn tính. Đồng thời, nghiên cứu chỉ ra rằng, để HCN từ HCNT không gây

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tác động tiêu cực đến sức khỏe cộng đồng, nồng độ cyanide trong HCNT nên là 2.73 mg/l, thay vì 20 mg/l như được đưa ra trong EIA của dự án.

Từ khóa: AERMOD; hydro xyanua; mỏ vàng; mô phỏng; hồ chứa nước thải.

1. Introduction

HCN is the most toxic form of cyanide [1]. People can be seriously harmed if exposed to HCN. It can have acute and chronic effects on individual and public health and could prove lethal, if inhaled; however, the amount of harm would depend on the concentration of HCN in the air and the duration of exposure [2]. Once it enters the lungs or stomach, HCN enters the bloodstream. Some of it is changed to thiocyanate (SCN^-), which is less harmful and leaves the body in the urine via the urinary tract. Small amounts of HCN are converted to carbon dioxide, which leaves the body via the lungs while breathing. At low levels of exposure HCN and its products leave the body within 24 hours of exposure [3].

In gold processing, cyanide is often used to extract gold from gold-bearing ore [1, 4]. This is an effective and widely used extraction process used by over 90 % of the world's gold mines (GMs) [4]. Resulting cyanide contaminated waste product is released into a tailings storage facility (TSF). HCN is highly volatile so it readily evaporates. The surface areas of the TSF is open and exposed to the open air, thus allowing HCN to enter the atmosphere. Volatilization can occur at many different stages of the gold mining activity, such as at leach process tanks but major HCN volatilization (90%) takes place from the TSF [5].

Thailand's largest gold mine is in Phichit Province. According to the Environmental Impact Assessment (EIA) report of the mine, cyanide, which is used as a solvent to separate gold and silver from ore, would be discharged into the TSF with a total cyanide concentration, not exceeding 20 mg/l. The first TSF (TSF1) of the mine was built with a maximum tailing storage of 21 million tons and it is now essentially full. The second TSF 2 (TSF 2) was built in 2013 with an ultimate storage capacity of 60 million tons, and in future a third TSF will be required [6].

There are many and varied opinions regarding the impact of cyanide from the gold mine in Phichit on public health. Reports from a gold mine in Phichit concluded that people living around the mine are not adversely affected by HCN evaporating from mine [7-9]. Other opinions, data from a study conducted by Khon Kaen University [10] show that naturally occurring surface water has been contaminated with cyanide. Local residents have complained that the water from the environment is no longer fit for human consumption; and they experienced symptoms of central nervous system toxicity, such as weakness, headache and changes in taste and smell, more often than before the gold mine operating [11]. This causes great concern that the HCN emitted from TSF1 may be harming local people.

In order to clarify and test the veracity of these disparate opinions, the air dispersion modeling approach (AERMOD) was used in this study to assess the impact of HCN volatilization from TSF1 on the health of nearby communities. The results and findings of this study can be used as the basis of appropriate management for other gold mining projects in Thailand in the future.

2. Materials and Methods

The AERMOD model was used to simulate the dispersion of HCN from GM'sTSF1 around the GM plant. The HCN concentrations in the atmosphere at the center point of each community within the study area were determined. Then, the results were compared with Acute and Chronic Inhalation Reference Exposure Levels (RELs) of HCN by inhalation to determine the communities exposed.

This study assessed practices recommended in the EIA report on cyanide management for the GM'sTSF1 facility. Based on the acute and chronic exposure results, the recommended levels to prevent harm to public health were calculated. This data was compared to the concentration levels of total cyanide released into the TSF1 as assessed in the EIA report on TSF1. A comparison between the HCN exposure levels of people within communities living around the mine compound with the pH of HCN at different levels. The exposure is calculated at pH levels of 10 or higher and the actual pH which was found to be 6.9.

2.1. Study area, period, and population

Data from 2002 to 2011. This study used data from the period 2002 to 2011. It was over this period that gold mine in Phichit released cyanide-contaminated mine tailing and mine water into TSF1. The geographic area of the study is defined according to the reference point at GM with the coordinates (675740.33 m E, 1801160.39 m N), and the radius from the center point to the border of the study area, is 50 km. We estimated the numbers of the communities located in the study area by counting the number of center points of those communities in study area, with the result that there are 148 communities.

2.2. Pollutant dispersion

Dispersion model. We first estimated HCN concentrations in the air by using the U.S. EPA's AERMOD MPI Version 15181 dispersion model [12]. This model used information about the emission rates of HCN from the GM's TSF1, local meteorological conditions and some other local information, such as terrain data and the location of receptors to provide hourly and annual average concentrations at multiple locations corresponding to the center points of 148 communities.

Release source location. In this study, we simulated the dispersion of HCN from wet surface areas in the GM's TSF1 (328,060 m^2). The study assumed that the wet surface areas covered by mine waste from gold extraction process. With the continuous flow rate of mine waste from gold extraction into TSF was 29,232 m^3/day [7], the average thickness of mine waste in TSF after three days (half-life of HCN in solution [13], was 26.7 cm.

Emission data. To calculate the emission rate of HCN from TFS1 to the air, the theory of Fate and Transport of cyanide in solution [1], and Air-Gas exchange theory [14] were used. The emission rate data of HCN was calculated according to the following equations [5]:

$$N''_{HCN} = K_{OL,HCN}(\Delta C) \qquad (2.1)$$

where, N''_{HCN} is emission rate of HCN (g/m^2s); $K_{OL,HCN}$ is mass transfer coefficient of HCN (m/s) ; ΔC is concentration of HCN gradient across the film (mg/m^3).

HCN concentrations. The concentrations of free cyanide in the mine waste released to TSF1, according to [7] was almost 5 mg/l if the concentrations of weak acid dissociable (WAD) was 13.9 mg/l. Based on the cyanide characteristics of the gold mine in Phichit mine waste sent to the TSF1 and the data of average concentration of WAD in TSF1 in 2011 was 2.57 mg/l [8], assumed that the concentration of free cyanide in 2011 was 1.54 mg/l. This data assumed a constant free cyanide concentration in solution in TSF1 during the study period.

This study divided pH of solution into a five level scenario: level 1 – lower pH = 6.9, level 2 = 8.6, level 3 = 9.2, level 4 = 9.8, and level 5 =

11. Base on the effect characteristic of pH to percentage of HCN compared with free cyanide concentration, the proportion of HCN compared with free cyanide in TSFs at each pH level was assumed 100%, 75%, 50%, 25% and 0% respectively [1].

Mass transfer coefficient of HCN (K_{OL}) was calculated by following equation [5]:

$$1/K_{OL} = 1/K_L + RT/H_{HCN} \times K_g \qquad (2.2)$$

where: R is the universal gas constant (atm m^3 $(mol\ K)^{-1}$; T is the absolute temperature (K); K_g is the gas phase mass transfer coefficient (m/s); H_{HCN} is the Henry's Law constant for equilibrium partitioning of HCN between the liquid and gas phases (pa m^3)/mol), was calculated according to the following equations [1]:

$$\text{Log } H_{HCN} = -1272.9/T + 6.238 \qquad (2.3)$$

where, $K_{L,HCN}$ is the liquid phase mass transfer coefficient (m/s); To estimate the $K_{L,HCN}$ study used the following equations [15, 16]:

$$K_{L,HCN} = K_{L,O}(32/M_{HCN})^{0.25} \qquad (2.4)$$

where, M_{HCN} the molecular weight of HCN (g/mol), and $K_{L,O}$ the oxygen-transfer coefficient in the water phase (m/s) [1]

and $K_{g,HCN}$ was calculated as the following equation:

$$K_{g,HCN} = K_{g,H2O}(18/M_{HCN})^{0.25} \qquad (2.5)$$

where, $K_{g,HCN}$ is the gas-film mass transfer coefficient and $K_{g,H2O}$ is the water vapor transfer rate in air (m/s) [1].

2.3. Exposure assessment

The exposure of people to HCN and its potential health effects was assessed based on comparisons between HCN concentrations in the air at the center point of each community with the referent dose of HCN. Data from the AERMOD model was used to calculate the concentrations of HCN at 148 receptor locations within the 50 km radius of the center point. For each pH scenario, the concentration of HCN at the receptor point is taken in two average emission period time options: hourly averaging dispersion period time option (ADPTO) to compare with acute inhalation RELs, and annual ADPTO was used to compare with chronic inhalation RELs. The highest serious with acute effect was assessed in this study, so the first highest hourly value for an average period of time option in the AERMOD model was chosen.

Data concerning the effect of HCN. In this study, the most recent data concerning the effect of HCN on public health with the minimum concentration of acute inhalation RELs was 340 $\mu g/m^3$ and for chronic inhalation RELs was 9 $\mu g/m^3$ [17], with details of those organs of the body most effected.

In addition, on each scenario of pH (4 pH levels) the number of communities exposed to HCN on each of the 3 terrain elevation levels: flat areas (<50 m), hilly areas (50 m to 100 m) and mountain areas (>100m) were considered.

3. Result and Discussion

3.1. The emission rate of HCN from TFS1

The emission rate of HCN. The emission rate of HCN from GM's TSF1 was considered using the following method: pH of the solution in TSF1 was level 1, the average temperature of study area was 302 K, and free cyanide concentration in TSF1 was 1.54 mg/l. The result of the emission rate of HCN under several pH levels are shown in the Table 1.

The emission rate pattern of HCN parallels with the pattern of free cyanide concentration under the effect of pH. As mentioned in Method section, the proportion of HCN compared with free cyanide in TSF1 at each pH level was assumed 100%, 75%, 50%, 25% and 0% respectively [1]. From the above, the emission rate of HCN for each pH level is given in the Table 1. The result from Table 1 shows that, the emission rate of HCN from

TSF1 decreased gradually with the increase of the pH of mine water in TSF1. When the pH is higher than 11, HCN in TSF1 is no longer volatile.

Table 1. The emission rate data of HCN from TFS1 into the air under several pH levels

pH level	Level 1	Level 2	Level 3	Level 4	Level 5
% HCN/CN^-	100	75	50	25	0
ΔC_{HCN} (g/m^3)	1.54	1.16	0.77	0.39	0
K_{OL} (m/s)	2.45×10^{-5}	2.45×10^{-5}	2.45×10^{-5}	22.45×10^{-5}	2.45×10^{-5}
N''_{HCN} (g/m^2s)	3.77×10^{-5}	2.82×10^{-5}	1.88×10^{-5}	9.41×10^{-6}	0

3.2. General dispersion of HCN from TSF1

The effect of distance on the concentration of HCN in the air. Simulation results from AERMOD model showed that, the concentration of HCN in the air declined gradually with increasing distance from the release source to the receptor point (Figure 1). For all pH levels, the maximum concentration of HCN in the air was always in TSF1 area. The two communities always exposed to HCN with the highest concentration in the air were Khao Chet Luk and Thai Dong, the two nearest communities to the TSF1. Communities exposed to the lowest atmospheric concentration of HCN were communities located farthest away from TSF1, in particular, communities in mountain areas and in the North East of GM.

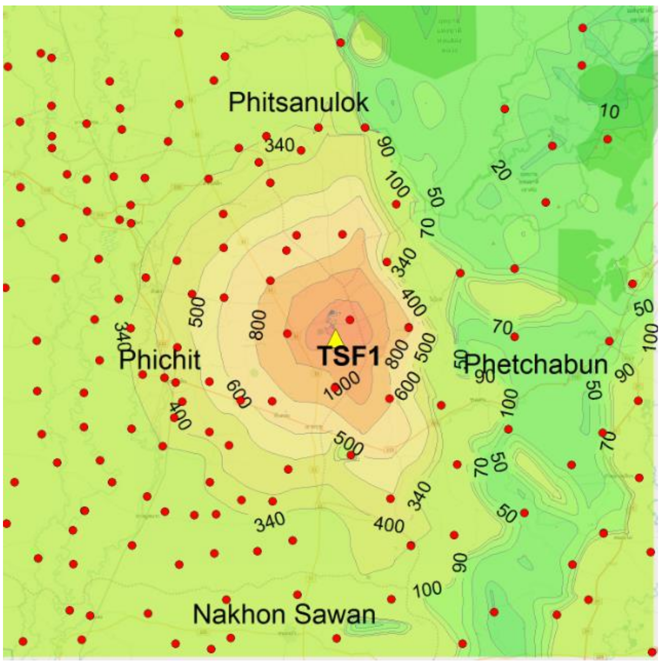

Figure 1. Hourly dispersion of HCN from TSF1 into the air under the scenario of a pH of 6.9 and a free cyanide concentration of 2.39 mg/l. The red circles are the subdistrict's populated places. The color shows the concentration in the unit of $\mu g/m^{-3}$.

To conclude, the simulation result on the dispersion HCN from GM's TSF1' by using the AERMOD model corresponded with the hypothesis of the AERMOD model. Therefore, these results may be confident enough to apply in practical work.

3.3. Health effect

3.3.1. Acute HCN exposure

In general, communities have long been exposed to acute inhalation RELs at every pH level, with the number decreasing as the pH level increased (Figure 2). The communities exposed to inhalation RELs were 42 for pH level 1, 21 for pH level 2, 10 for pH level 3 and 1 for pH level 4, respectively. As far as the exposure area, there was 2,274 km^2 exposed to acute levels when the pH of the solution in TSF1 was lower than 7, and when the pH level increased from 9.24 to 11 the area exposed with acute effect concentration was 87 km^2.

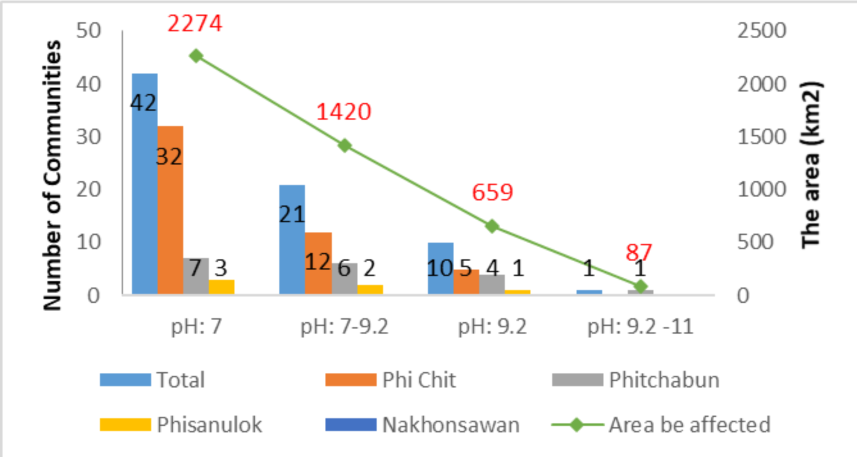

Figure 2. The number of communities and areas exposed to Acute Inhalation RELs of HCN

3.3.2. Chronic HCN exposure

Only two communities were exposed to levels of HCN in excess of the chronic inhalation RELs (one in Phichit and one in Phitchabun), when the pH of the solution in TSF1 was at level 7. At other pH levels (higher than 7) of the solution in TSF1, only a limited area around the gold mine in Phichit has levels of exposure within chronic inhalation REL's levels (Figure 3).

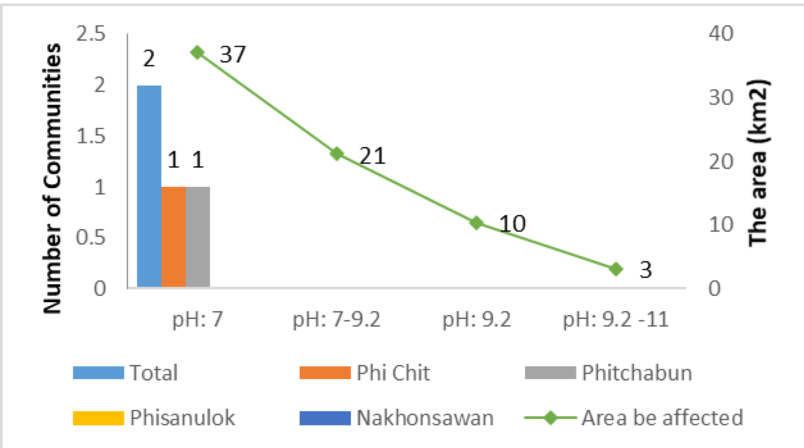

Figure 3. The number of communities and areas exposed to Chronic Inhalation RELs of HCN

To conclude, the study area exposed to acute and chronic inhalation RELs of volatile HCN that evaporated from GM's TSF1 in the period from 2002 to 2011. The number of communities and the areas exposed to RELs declined if: the distance from TSF1 to the receipt point increased, or the wind speed and volume increased and the wind direction changed, or pH of the HCN solution in TSF1 increased. At pH level 9.24 – 11, only one community is exposed to acute inhalation RELs, and only a limited area around GM has levels of exposure within the parameters of chronic inhalation REL's levels.

3.4. An assessment of practices recommended in the EIA report for TSF1 on cyanide management

The results from the AERMOD model used in this study showed that the concentration of total cyanide released into the TSF1 was assessed in the EIA Report at 20 mg/l, pH level 4, which is too high. Based on the emission rate of HCN from TSF1 (Table 1) and the number of communities exposed to the acute effects of HCN (Figure 2), this study determines the emission rate of HCN to prevent harm to public health (Figure 4). The result recommends a level of 2.73 mg/l, to prevent harm to public health when pH is at level 4. This current study investigated the HCN levels discharged into TSF1, and found that the concentration of total cyanide released into TSF1, is about seven times higher than the recommended level. Therefore, the recommended limits of concentration of total cyanide, as stated in the EIA, cannot be considered appropriate.

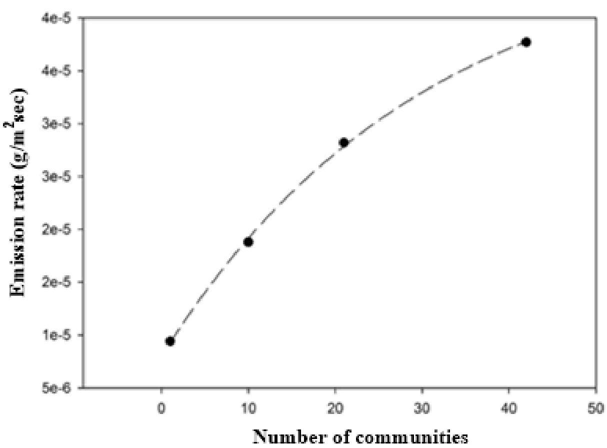

Figure 4. Corresponding between emission rate of HCN in TSF1 and the number of community exposed acute inhalation REFs

4. Conclusion

In conclusion, it is apparent that the GM has failed to achieve the limits laid down in the EIA, and this has had a detrimental effect on the 42 communities in the vicinity. These communities would not have been so affected if proper management and control procedures had been in place during the period studied. It was also found that the recommended limits and levels of the concentration of total cyanide, stated in the EIA, cannot be considered appropriate, and it is recommended that they be revised to a significantly lower level.

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