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Prediction model for cyanide environmental pollution in artisanal gold mining area by using logistic regression

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Introduction

The use, fate and behaviour of cyanide in two catchments areas affected by ASGM in Burkina Faso have been investigated. It was found that up to 20 kg/week of cyanide could be illegally used in one catchment area for gold processing. Cyanide-containing leachate is then directly released into the environment without any treatment or control. FCN accumulates around the cyanide-processing zones, whereas some is also progressively transported to the catchment outlet through surface runoff and infiltration, which pollutes surface water, groundwater and soil within the catchment. However, the processes that control the transport of FCN are not sufficiently understood to allow the identification and targeting of pollution risk zones for the implementation of a remediation plan. In this regard, the Geographic Information Systems (GIS) could be useful in assessing cyanide pollution risk.

The aim of the present study is to(i) create a cyanide pollution risk map for ASGM sites by applying the LR method, (ii) identify possible risk factors that may explain the spatial distribution of cyanide contaminated areas, and (iii) identify areas of high risk so that appropriate remediation actions can be taken.
We first developed a conceptual model of the spatial distribution of cyanide pollution risk. Factors relevant to cyanide pollution transport were then identified and probability maps for cyanide pollution risk were created and analysed.

Methodology

Two ASGM sites were selected for modelling cyanide contamination using LR based on their climatic and environmental conditions and mining activity.

Two samples were collected from each site, in March 2015 and in April 2016.More than thirty points covering the cyanidation zones, catchment areas boundaries and outlets and the mining villages were selected for soil sampling

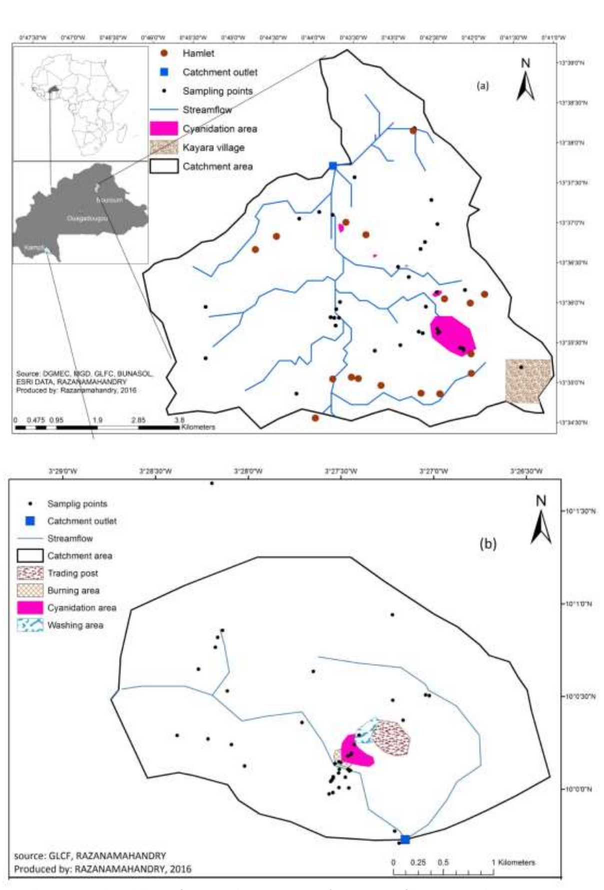

Figure 1: Site locations and sampling points: (a) Zougnazagmiline, (b) Galgouli

Free cyanide was measured and modelled by using Logistic regression (LR) model. LR is used to explain an observed or dependant variable through one or more independent predictor, or explanatory variables.

$$p = \frac{1}{1+e^{-y}}$$

p: probability of occurrence of an event, which is cyanide contamination in this case of this study. P was subdivided in 5 classes (Very low, low, moderate, high, very high) every 20 %.

$$y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n$$

$ß_i$: coefficients of the explanatory variable
X_i: Explanatory variable

The procedure for modelling cyanide pollution was done in three steps as shown in Figure 2.

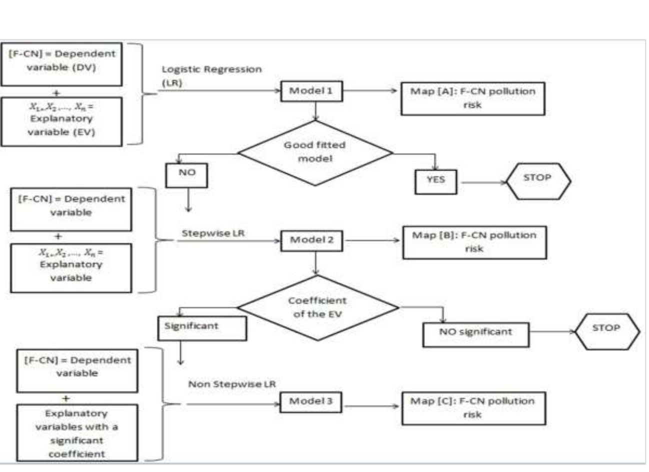

Figure 2: Methodological approach for building the model of cyanide pollution

The model input data comprised the dependent variable and the explanatory variables as shown in Table 1

Table 1: Model data

Data	Type	Variable	Coverage	Source	Cell size(X,Y),angular unit degree
Geology	Continuous	Independent	2013	DGMEC[a]	0.022689,0.022689
Rainfall (mm)	Continuous	Independent	1970 - 2012	MGD[b]	0.024955,0.024955
Temperature (°C)	Continuous	Independent	1970 - 2012	MGD	0.024955,0.024955
Topographic elevation (m)	Continuous	Independent	2008	GLCF[c]	0.000833,0.000833
Land use	Continuous	Independent	2010	BUNASOL[d]	0.000280,0.000280
Soil type	Continuous	Independent	2010	BUNASOL	0.000289,0.000289
Soil pH	Categorical	Independent	2015-2016	Present study	0.00022,0.00022
Soil Conductivity (mS cm^{-1})	Categorical	Independent	2015-2016	Present study	9e-005,9e-005
Distance to cyanidation Ponds (m)	Categorical	Independent	2015-2016	Present study	8.6e-005,7.99e-005
F-CN Concentration (mg L^{-1})	Categorical	Dependent	2015-2016	Present study	7.99e-005,7.99e-0.005

Results and discussion

Table 2 summarizes the LR model of each area.
In Zougnazagmiline, the three models have an AUC around 0.8 and p-values of 0.42, 0.05 and 0.01 for Model 1, Model 2 and Model 3, respectively. The Loglik-ratio of Model 3 was lower than that of Model 1 and Model 2 (-18.96 < 0.00). All models have good AUC values greater than 0.7. Only the p-value of Model 2 and Model 3 are equal to or less than 0.05.
In Galgouli, the AUC of Model 1, Model 2 and Model 3 are 0.76, 0.74 and 0.69, respectively,
whereas their respective p-values are 0.61, 0.05 and 0.02. In regard to the AUC value, good model fit has been established except for Model 3 in Galgouli., which indicates that the explanatory variables are related to the spatial distribution of cyanide contamination [*Lin et al.,* 2011].

Table 2: The p-value and the AUC values for each model

Site	Model name	Loglik-ratio	Deviance	X^2	Explanatory variable number	p-Value	AUC
Zougnazagmiline	**Model 1**	0.00	32.21	9.18	9	0.42	**0.79**
	Model 2	0.00	34.85	9.40	4	**0.05**	**0.78**
	Model 3	-18.96	37.92	6.33	1	**0.01**	**0.75**
Galgouli	**Model 1**	0.00	46.63	7.20	9	0.61	**0.76**
	Model 2	0.00	50.26	3.58	2	**0.05**	**0.74**
	Model 3	0.00	52.25	1.59	1	**0.02**	**0.69**

Figure 3 shows the ROC curves for the three models at each site. In terms of the p-value in both sites, the level of confidence increases from Model 1 to Models 2 and 3 (from 58 and 31 % to more than 95 %). Model 1 of both sites contains more explanatory variables than the other models. The p-values of the models improved as insignificant explanatory variables number were removed. In both sites, Model 1 has a p-value greater than 0.05, althoughModels2 and 3 have p-values less than 0.05. Model 1 is not significant and was therefore removed from consideration.

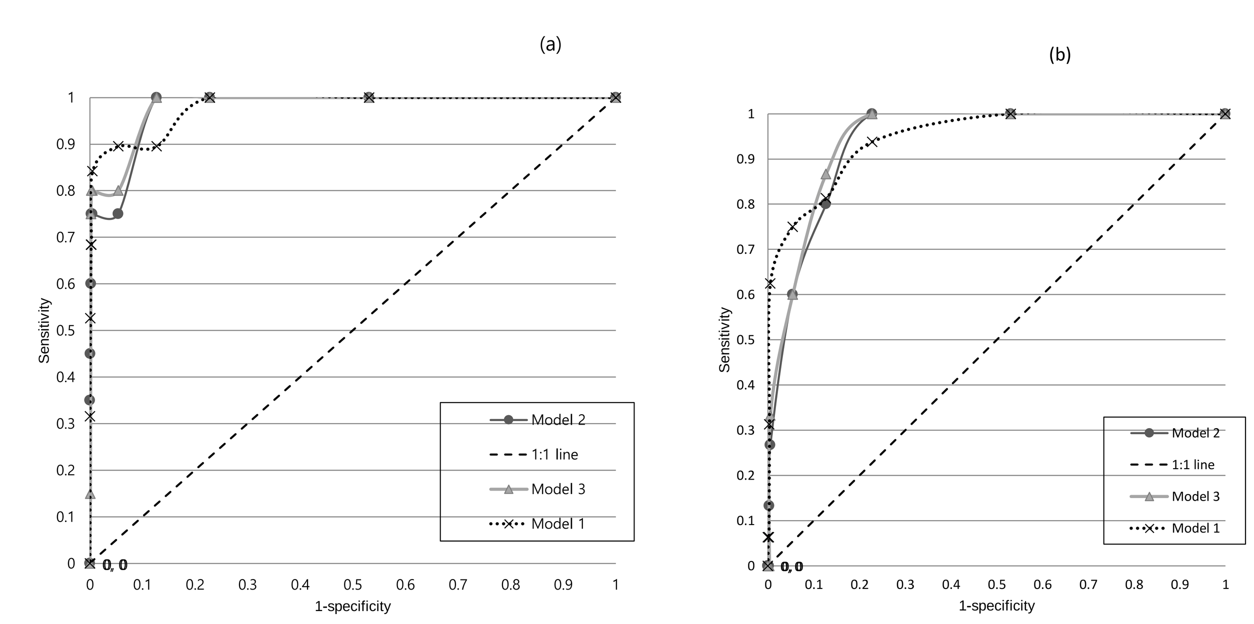

Figure 3: ROC curves for the (a) Zougnazagmiline site and (b) Galgouli site

Figures 4 and 5 show the probability maps of the spatial distribution of cyanide contamination in Zougnazagmiline and Galgouli.
In Zougnazagmiline, cyanide contamination probability varies from very low to moderate near the catchment boundary, irrespective of the model. Figure 4 [Model 1] displays an over-predicted model for cyanide contamination hazard. In fact, the very high probability (p = 0.80 - 1) for cyanide contamination covers over 50% of the catchment area. Figure 4 [Model 2] and [Model 3], however, more precisely defines the zones that present a very high risk of cyanide contamination, which represent 30% and 20% of the total surface area, respectively.
The zones with the greatest probability are near the cyanidation zones, which was expected. Part of the river bank also has a high chance of cyanide contamination, which is due to the river bank often containing clay, in which FCN is likely to be present.

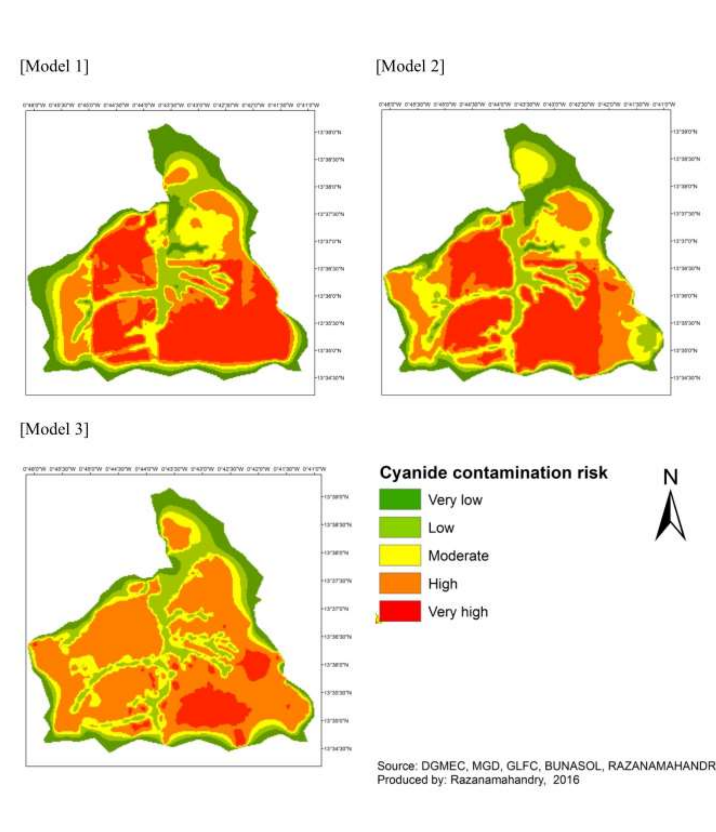

Figure 4 : Probability map for cyanide contamination risk at the North.

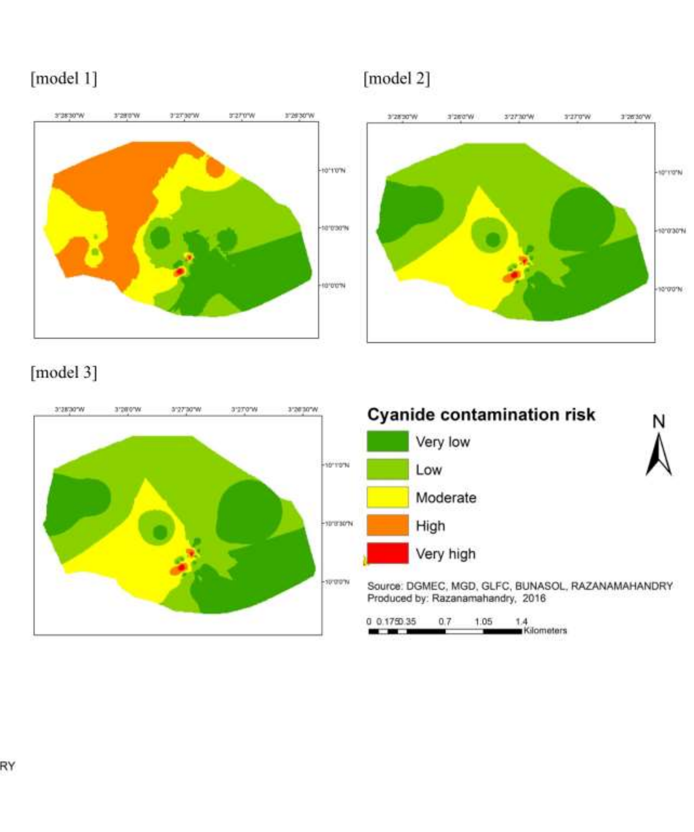

Figure 5 : Probability map for cyanide contamination risk at the South.

Model 1 of Galgouli(Fig. 5)is also over-predicted. The areas of high probability of cyanide contamination cover about40% of the total surface area. Model 2 and Model 3 in Figure 5 and give almost the same spatial distribution of cyanide in soil, with only 5% of the catchment area having a very high probability of cyanide contamination, which corresponds to the cyanidation zone. The explanatory factors selected in Model 2 and Model 3 are significantly correlated with and explain the spatial distribution of cyanide.

The area of predicted FCN contamination represents less of the catchment at Galgouli (5%) than at Zougnazagmiline (20%).
Botz et al. (2015),Bureau et al. (2011) and Kjeldsen (1999) have reported that FCN could take the anion cyanide form (CN^-) that reacts with metal cations under high pH conditions. Furthermore, Nsimba (2009) and Wong-chong et al.(2006) found that FCN takes the gaseous form HCN and could easily volatilize under acidic conditions. The climate of Zougnazagmiline is arid with a basic soil, whereas Galgouli is humid with acidic soil. Therefore, CN^- is the dominant component of FCN in Zougnazagmiline whereas HCN is more available in Galgouli. Our results suggest that FCN accumulation in arid Zougnazagmiline and volatilisation in humid

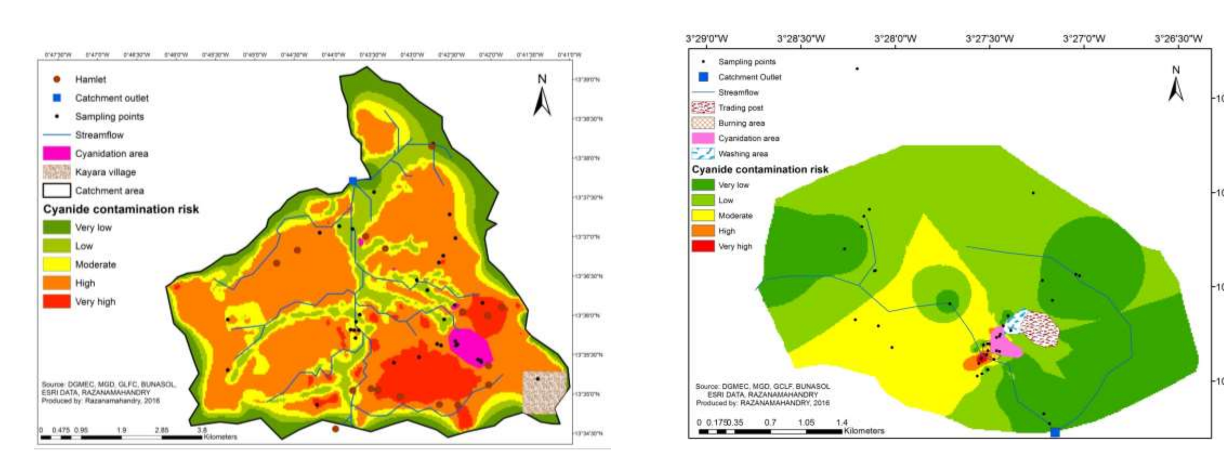

Figure 6: Cyanide contamination exposure (a) in Zougnazagmiline and (b) in Galgouli

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Conclusion

ASGM is the primary economic activity of the people of Zougnazamiline and Galgouli. Since water and soil contamination by cyanide is widespread at these sites, it was deemed necessary to determine the most vulnerable areas in order to prioritize restoration of the degraded ecosystem. Environmental factors related to the spatial distribution of cyanide have been evaluated. Three predictive models using LR were created for each site, which have different climate conditions and soil characteristics. The most important factors influencing the FCN distribution are the soil type in Zougnazagmiline and the soil conductivity in Galgouli. Therefore, when the zone is arid, only the soil type would influence the FCN distribution but if it is humid, both the soil type and the soil conductivity would be the main influencing parameter. Environmental factors such as the distance from cyanidation zones, topographic elevation and land use are likely to increase cyanide contamination risk. Since the soil conductivity and soil type are dependent upon the soil composition, that aspect needs to be investigated in depth to fully understand FCN distribution in ASGM affected areas. Moreover, the LR model should also be tested in the zone under Soudanese-Sahelian climate to determine the main parameters that influence the FCN distribution in semi-arid areas. This would then allow for the prediction of FCN distribution for any ASGM area in Burkina Faso based on its climate and soil characteristics.

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