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Evaluation on Ecological Risks of Soil Heavy Metals in a Certain Area of Sichuan by Improved Fuzzy Mathematics Method

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Abstract

Taking a certain area in Sichuan Province as the object of this study, this paper adopts fuzzy mathematics method to make an evaluation on ecological risks of heavy metal in soil of this area. On calculation of factors' weights, the traditional method of giving weight according to pollutants' concentrations fails to consider the toxicity of heavy metals, and can't reflect their actual ecological effect. With reference to the toxicity coefficient in potential ecological risk index evaluation, this article revises the traditional fuzzy mathematics evaluation model and puts forward a new method to calculate factors' weight by incorporating toxicity levels in weight setting. The results of this study indicate: surface soil of this area was good in general, with 91.2% samples belonging to the first level, 7.77% samples belonging to the second level, and only 1.03% belonging to the third level. Compared with the results of the evaluation method of the reality content of soil, soil quality is better than the results of the quantitative evaluation, and is closer to the actual local conditions.

Keywords

Fuzzy Mathematics; Heavy Metals; Soil Contamination; Evaluation

1. Introduction

Heavy metal pollution of surface soil refers to the phenomenon that human activities cause significant higher concentration of heavy metals in surface soil compared with the background level, ecological damages and deterioration of environmental quality. In recent years, an increasing number of issues of heavy metal pollution have been reported, meanwhile, various methods of evaluation of it have also been proposed. Based on former researches, this paper adopts integrated fuzzy mathematics evaluation model to assess heavy metal pollution in surface soil of a certain area in Sichuan province. The results of assessment could provide basis for land restructuring and industry restructuring.

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2. Material and Methods

2.1. Materials

The study area, situated in Dakang town, Jiangyou city (31˚48'48" - 31˚52'35" N, 104˚39'51" - 104˚44'26" E), belongs to subtropical humid monsoon climate with average annual precipitation amount 1139mm, and annual average temperature 16.4˚C. In this area, ≥0˚C annual average accumulated temperature is 5844.6˚C, and ≥10˚C of the annual accumulated temperature is 5021.4˚C. Soil types are mainly purple soil and paddy soil, and the main vegetation type is subtropical coniferous forest. Agriculture is plantation-based, whose major agricultural products are rice, wheat, rape plant, corn, sweet potato, vegetables.

2.2. Study Methods

1) *Sample Collection and Analytical Methods*

According to the principles of representation, homogeneity and controllability, 5 soil column samples were collected from the same soil type and land use type within a radius of around 30 m near the sampling point and then were blended into a combination of soil column sample. Among them, the sampling density is about 16 samples/km^2 and sampling medium is 0 ~ 20 cm soil column to the surface. Regional field geochemical basic survey was taken in this area. 296 sampling points were selected from the surface soil, consisting of 179 from purplish soil and 117 from paddy soil. The soil samples were tested and analyzed by Chengdu Research Center for Land and Mineral Resources Supervision and Test, Ministry of Land and Mineral Resources. Detection methods and limits of heavy metals are shown in **Table 1**.

2) *Comprehensive Fuzzy Mathematics Evaluation Method*

Comprehensive Fuzzy Mathematics Evaluation Method can exclude influence from subjective factors and keep objective. Therefore, it is effective to solve the fuzzy boundary among the degrees of heavy metal pollution and control the evaluation result errors. These can be widely applied to evaluation of soil environmental quality. Given that heavy metal pollution is gradual and fuzzy, pure quantitative method is unreasonable to distinct and quantify degrees of pollution with a clear line. While, fuzzy mathematics method is reliable since it can describe the progression and fuzziness of the pollution.

3) *Standard for Heavy Metal Elements Evaluation*

Based on soil environmental quality standard GB15618-1995, soil environment quality is evaluated by selecting metal elements, such as: As, Cd, Cr, Cu, Hg, Pb, Ni, Zn, etc. The standard values can be seen from **Table 2**.

3. Detection Results and Analysis by Taking Fuzzy Mathematics Method

3.1. Heavy Metal Element Content-Comprehensive Evaluation

296 samples were selected from the surface soil in the study area. The characteristics of heavy metal elements content in the study area can be seen from **Table 3**. The table shows that a majority of elements are within narrow limits, except for As, Cd, and Hg.

Adopting MAPGIS spacial analysis, this paper generates **Figure 1**—a miniature of comprehensive evaluation by employing grid method to superimpose the heavy metal content in surface soil from the study area. The principle of superposition is to disqualify a higher level with a single lower value. If all indicators belong to first-level soil, it will be the first one—clearing zone—after the superposition. If there is an indicator belongs to second-level soil, it will be the second one—normal zone. Similarly, if there is an indicator belongs to the third or even higher level, it will be the third one—contaminated zone.

As is shown in **Figure 1**, first-level soil occupies 12.7%, second-level 55.7% and third-level 31.6%.

3.2. Fuzzy Mathematics Evaluation Methods

Given there are three steps for fuzzy mathematics comprehensive evaluation, combined with the actual situation of this study area, this paper discusses:

Step 1, 8 common heavy metals in soil are selected as evaluation indicators, namely Cd, As, Hg, Cu, Pb, Cr, Zn, Ni.

Table 1. Detection methods and detection limits for heavy metal elements (mg·kg^{-1}).

Element	Method	Detection Limits	Element	Method	Detection Limits
Cd	ICPMS	0.03	Hg	AFS	0.003
As	AFS	0.5	Pb	X fluorescence	2
Cr	X fluorescence	5	Ni	X fluorescence	2
Cu	X fluorescence	1	Zn	X fluorescence	4

Table 2. Soil environmental quality standard values (mg·kg^{-1}).

Element	Grade I	Grade II			Grade III
	Back ground value	pH < 6.5	pH 6.5-7.5	pH > 7.5	
Cd	≤0.2	0.30	0.30	0.60	1.0
Hg	≤0.15	0.30	0.50	1.0	1.5
As	≤15	30	25	20	40.0
Cu	≤35	50	100	100	400.0
Cr	≤90	150	200	250	400.0
Zn	≤100	200	250	300	500.0
Ni	≤40	40	50	60	200.0
Pb	≤35	250	300	350	500.0

Table 3. Characteristics of heavy metal elements content in the study area (mg·kg^{-1}).

Chemical parameters	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Min	1.88	0.06	60.10	14.00	0.02	18.50	21.30	45.30
Max	31.66	1.26	209.10	97.90	1.00	89.50	53.60	147.10
Mean	10.92	0.32	87.36	31.12	0.09	36.22	33.75	90.36
SD	5.23	0.15	17.99	10.48	0.06	9.80	5.48	22.19

*n = 296.

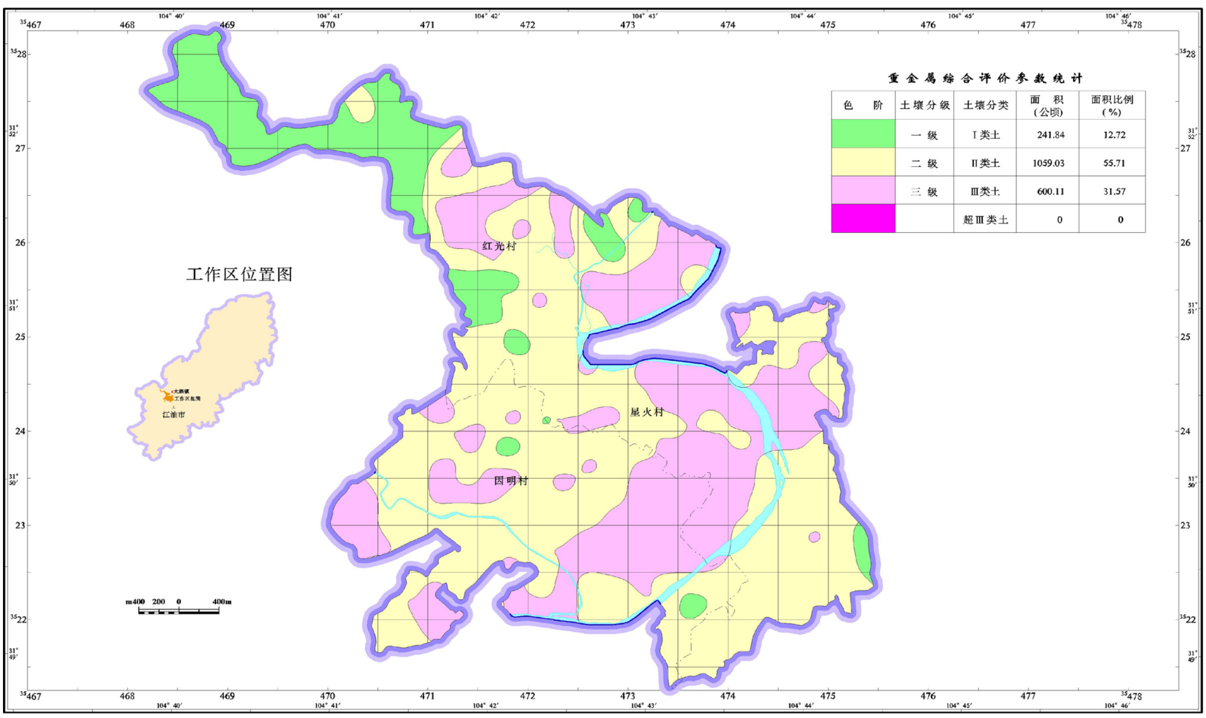

Figure 1. Comprehensive evaluation of heavy metal elements.

Step 2, fuzzy relationship matrix is established based on membership functions of evaluation factors, and then can be adopted to calculate the weighted values of evaluation indicators.

Step 3, new fuzzy evaluation model is employed to calculate and generate the result.

1) *Formation of membership function and fuzzy matrix*

Membership function can be used to describe the fuzzy boundary of the contaminated soil. Defining soil environmental quality standard values in **Table 2** as inflection points, each membership function of heavy metal contamination at various PH can be obtained by using the piecewise linear functions. The following are the 3 piecewise functions that are commonly used to describe heavy metal contamination in soil.

Membership function of certain heavy metal in first-level soil is

$$u(x_i)=\begin{cases}1 & x_i \le a_i \\ (b_i-x_i)/(b_i-a_i)\,| & a_i < x_i < b_i \\ 0 & x_i \ge b_i\end{cases} \tag{1}$$

Membership function of certain heavy metal in second-level soil is

$$u(x_i)=\begin{cases}0 & x_i \le a_i, x_i \ge c_i \\ (x_i-a_i)/(b_i-a_i) & a_i < x_i \le b_i \\ (c_i-x_i)/(c_i-b_i) & b_i < x_i < c_i\end{cases} \tag{2}$$

Membership function of certain heavy metal in third-level soil is

$$u(x_i)=\begin{cases}0 & x_i \le b_i \\ (x_i-b_i)/(c_i-b_i)\,| & b_i < x_i < c_i \\ 1 & x_i \ge c_i\end{cases} \tag{3}$$

Among the above piecewise functions, xi is the measured value, while a_i, b_i, c_i are standard values for first-, second- and third-level environment quality respectively.

According to the need for heavy metal evaluation in the study area, the indicator set U = {Cd, Hg, As, Cu, Pb, Cr, Zn, Ni} and evaluation set V = {first, second, third} are established.

According to various pH values of the 296 surface soil samples selected from the study area, membership function of each sample can be established by adopting the above formula. These 296 membership functions are used to form 8*3 fuzzy relation Matrices R.

$$A=\begin{bmatrix}1 & 0 & 0 \\ 0 & 0.9286 & 0.0714 \\ 0.9200 & 0.0800 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \\ 0.9995 & 0.0005 & 0 \\ 1 & 0 & 0\end{bmatrix}$$

For ease of calculation, firstly, samples are divided into three intervals—pH < 6.5, 6.5 ≤ pH ≤ 7.5, pH > 7.5—according to their pH values. Then, statistical calculations are done by employing different bi values according to various pH values. Finally, fuzzy matrices are established by obtaining membership functions of each sample. Taking No. 5 sample as an example, **Table 4** shows pH value and heavy metals contents of a certain topsoil sample from the study area.

2) *Calculation of Weighting Factors*

There are a number of ready methods for deciding factors' weight. But these traditional methods adopt calculation of excessive concentration of the pollutants empowerment and fail to consider the toxicity of heavy metals and to uncover the toxicity in low concentration of organism. Therefore, they cannot reflect the actual ecological effect. With reference to the toxicity coefficient in potential ecological risk index evaluation, this article revises

Table 4. H and heavy metals contents of a certain topsoil sample from the study area.

Sample number	pH	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
15	6.33	11.2	0.35	94.8	34.1	0.08	35.0	35.1	84.3

*Except pH, all are $mg \cdot kg^{-1}$.

puts forward a new method to calculate factors' weight by incorporating toxicity levels in weight setting.

$$W_i = (Y_i / F_i) / \sum_{i=1}^{n} (Y_i / F_i) \tag{4}$$

$$Y_i = \frac{X_{ki} / (\sum_{j-1}^{m} C_{ij} / m)}{\sum_{i=1}^{n} \left[X_{ki} / (\sum_{j=1}^{m} C_{ij} / m) \right]} \tag{5}$$

In the above functions, F_i is toxicity level index of the ith pollutant factor, X_{ki} is the measured value of a certain sample, C_{ij} is the standard value at a certain level, W_i is the weighted value of the ith factor ($\sum_{i=1}^{n} W_i = 1$, $\sum_{i=1}^{n} Y_i = 1$), Y_i is the pollutant concentration of the ith heavy metal, m is the number of classification, and n is the number of evaluation indices. Here m is 3 and n is 8.

The value of F_i is decided on the following two aspects: one is standardized coefficients of heavy metals appointed by Hakanson; another is the ranking of toxicity coefficients. According to the principle that the higher the toxicity of heavy metal is, the lower the index should be, this paper modifies the ranking of toxicity coefficients. By assuming that two have the equally important position in determining the value of F_i, toxicity coefficients in potential ecological evaluation of Hakanson are modified as follows:

$$F_i = \left(F_i^1 + F_i^2 \right) / 2 \tag{6}$$

$$F_i^1 = \frac{N_i}{n} \tag{7}$$

$$F_i^2 = \frac{-1}{D_{\max} - D_{\min}} \left(D_i - D_{\max} \right) \tag{8}$$

In (6), (7), (8), F_i^1 is the ith toxicity coefficients ranking index, F_i^2 is the ith toxicity index calculated by linear structure based on standardized coefficients of heavy metals appointed by Hakanson, n is the number of indices, N_i is toxicity ranking index of the ith factor, D_i is toxicity ranking index of the ith factor, D_{max} is the maximum toxicity coefficient, D_{min} is the minimum of the toxicity coefficient. Therefore, NHg=1, NCd=2, NAs = 3, NCu = NPb = 4, NCr = NNi = 5, NZn = 6, n = 8; D_{max} = 40, D_{min} = 1.

According to formula 6 to 8, FHg = 0.0625, FCd = 0.2532, FAs = 0.5721, FCu = FPb = 0.6987, FCr = FNi = 0.7997, FZn = 0.875.

Tables 5-7 are the heavy metal's weight distribution at various pH values.

3) *Fuzzy Evaluation Calculation and Result Generation*

Common evaluation models can be classified into two: one is to highlight a single decisive function model, such as single factor model and dominated factor model; another is a model that reflects a combined effect of participating factors, such as weighted average model and geometric average model. To satisfy the needs of this paper, weighted average model is adopted.

$$b_j = \sum_{i=1}^{n} w_i r_{ij}, \ j = 1, 2, \cdots, m \tag{9}$$

In Formula (9), b_j reflects membership of the evaluation result to the jth ranking, w_i is the correspongding weighted value, r_{ij} the corresponding element in fuzzy matrix R of fuzzy relationship, n is the number of participating factors, m is the number of rankings. Here m is 3.

Table 5. Weight of each heavy metal in topsoil of the study area when pH < 6.5.

Sample number	WAs	WCd	WCr	WCu	WHg	WNi	WPb	WZn
1	0.1867	0.1893	0.0921	0.0418	0.2975	0.0862	0.0378	0.0686
2	0.1838	0.1696	0.0920	0.0433	0.3129	0.0931	0.0348	0.0705
3	0.1619	0.2269	0.0873	0.0393	0.3001	0.0839	0.0331	0.0675
…	…	…	…	…	…	…	…	…
143	0.1806	0.2020	0.0984	0.0421	0.2816	0.0911	0.0335	0.0707
144	0.1731	0.2170	0.0983	0.0393	0.2867	0.0866	0.0326	0.0664
145	0.1899	0.1721	0.1034	0.0427	0.2910	0.0963	0.0326	0.0720

Table 6. Weight of each heavy metal in topsoil of the study area when 6.5 ≤ pH ≤ 7.5.

Sample number	WAs	WCd	WCr	WCu	WHg	WNi	WPb	WZn
63	0.0521	0.3428	0.1000	0.0615	0.2022	0.1125	0.0313	0.0976
70	0.1063	0.3516	0.0715	0.0339	0.2937	0.0622	0.0317	0.0491
80	0.0783	0.4289	0.0850	0.0368	0.2126	0.0776	0.0295	0.0513
…	…	…	…	…	…	…	…	…
113	0.1191	0.3905	0.0856	0.0486	0.1935	0.0732	0.0320	0.0575
125	0.1059	0.5785	0.0401	0.0238	0.1450	0.0563	0.0160	0.0344
127	0.1418	0.3586	0.0643	0.0320	0.2619	0.0721	0.0240	0.0453

Table 7. Weight of each heavy metal in topsoil of the study area when pH > 7.5.

Sample number	WAs	WCd	WCr	WCu	WHg	WNi	WPb	WZn
13	0.1565	0.3277	0.0637	0.0378	0.2617	0.0656	0.0316	0.0554
49	0.1120	0.4285	0.0877	0.0505	0.1227	0.0948	0.0334	0.0704
75	0.1172	0.3393	0.0897	0.0564	0.1804	0.1021	0.0328	0.0821
…	…	…	…	…	…	…	…	…
103	0.1750	0.3707	0.0752	0.0339	0.1695	0.0819	0.0278	0.0660
104	0.1533	0.3444	0.0762	0.0467	0.2172	0.0770	0.0280	0.0572
107	0.1360	0.4924	0.0690	0.0308	0.1141	0.0735	0.0257	0.0585

Adopting the above formulas, vector B = {b1, b2, b3} can be obtained. Based on the principle of maximum membership, the maximum is the final evaluation result of the corresponding rank.

As can be shown in **Table 8**, the values of b in 189 soil samples at pH < 6.5 can be calculated by adopting the above formulas. The results show that the quality of 173 samples belong to the first level, while maximum membership of 14 samples belongs to the second level and 2 belongs to the third level.

In **Table 9**, results of the values of b in 54 soil samples at 6.5 ≤ pH ≤ 7.5 show that 50 samples are the first level, while 3 are the second level and 1 is the third level.

In **Table 10**, results of the values of b in 53 soil samples at pH > 7.5 show that 47 samples are the first level, while 6 are the second level.

4. Conclusions

From what has been discussed above, we can safely draw the conclusion that the method that adopts fuzzy mathematics in evaluation is significantly superior to the previous methods. It is much closer to local reality. According to the evaluation results, the quality of soil is better in general. 91.2% belongs to the first level, 7.77%

Table 8. Uality evaluation result of topsoil in the study area when pH < 6.5.

Sample number	B1	B2	B3	Soil grade
1	0.9079	0.0921	0	I
2	1	0	0	I
…	…	…	…	…
19	0.3174	0.6015	0.0811	II
…	…	…	…	…
22	0.3163	0.6315	0.0522	II
…	…	…	…	…
102	0.4603	0.0731	0.4666	III
…	…	…	…	…
126	0.6701	0.3262	0.0037	I

Table 9. Uality evaluation result of topsoil in the study.

Sample number	B1	B2	B3	Soil grade
63	0.9539	0.0461	0	I
70	0.8437	0.1653	0	I
…	…	…	…	…
46	0.0700	0.5031	0.4269	II
…	…	…	…	…
77	0.4092	0.4500	0.1408	II
…	…	…	…	…
125	0.2279	0.1641	0.6080	III
…	…	…	…	…
127	0.4902	0.4511	0.0588	I

Table 10. Uality evaluation result of topsoil in the study area when pH > 7.5.

Sample number	B1	B2	B3	Soil grade
13	0.8570	0.1430	0	I
95	0.9525	0.0475	0	I
…	…	…	…	…
120	0.4566	0.5434	0	II
…	…	…	…	…
14	0.4682	0.3755	0.1563	I
…	…	…	…	…
12	0.3756	0.4649	0.1595	II
…	…	…	…	…
100	0.9637	0.0363	0	I

belongs to the second level and only 1.03% belongs to the third. While, in **Figure 1**, the first level soil occupies 12.7%, the second 55.7% and the third 31.6%.

The results vary because of adopting various evaluation results. The underlying reason is this evaluation method is more reasonable by adopting fuzzy mathematics to describe the gradients and fuzziness of heavy metal contamination through membership, compared with pure quantitative method.

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