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Modeling Analysis of Heavy Metal Evaluation in Complex Geological Soil Based on Nemerow Index Method

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Abstract: To accurately understand soil environmental quality and improve the problem of the traditional method, which is that it has a single evaluation factor and cannot reflect the overall condition of the soil, a complex geological soil heavy metal evaluation modeling method based on the Nemerow index method is proposed. Index evaluation methods, ArcGIS technology, and a human health risk assessment were carried out to obtain the spatial distribution of heavy metals in the soil and the current status of pollution accumulation. The comprehensive pollution index (CPI) method, geo-accumulation index (GAI) method, and potential ecological hazard (PEH) index were adopted to analyze the pollution degree of soil heavy metals. On this basis, the Nemerow index method was used to establish a complex geological soil heavy metal evaluation model, and the standard Nemerow index was calculated to complete the evaluation of heavy metal pollution in complex geological soils. The research results showed that this method could make the evaluation factors obtain reasonable scores and obtain more reasonable soil evaluation results.

Keywords: Nemerow index method; complex geology; soil heavy metals; comprehensive pollution index method; geo-accumulation index method

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1. Introduction

With the intensification of urbanization, various harmful substances caused by transportation, industrial discharge, sewage irrigation, etc. will enter the soil through atmospheric deposition, industrial "three wastes" discharge, and the abuse of agrochemicals. Soil environmental quality, which is especially affected by farmland soil pollution caused by heavy metal elements, is becoming an increasingly serious concern [1–3]. Heavy metal pollution comes with a variety of potential hazards. It can damage the normal function of the soil, hinder the normal growth of crops, cause a decline in crop yield and quality, lead to no harvest, affect the development of the agricultural economy, lead to the further deterioration of atmospheric and water environments, and most importantly, it can endanger human health through the food chain [4]. Therefore, understanding the current status of soil environmental quality and conducting targeted supervision are of great importance.

At present, there have been a number of reports on the problem of soil heavy metals. He B et al. proposed a spatial characteristic and risk assessment method for soil heavy metal pollution in a typical urbanized area [5]. Zhao J's team proposed an improved matter-element-extension-model-based evaluation method for heavy metal pollution in the cultivated soil in the Poyang Lake area [6]. Fan J. N et al., proposed a method for predicting and evaluating heavy metal pollution in the surrounding soil of key industries and enterprises based on the BP neural network [7].

Although the traditional method has been extensively applied in the evaluation of soil heavy metals, its evaluation results have the following limitations: the individual index scores are not continuous and there is a sudden change in soil quality. The Nemerow pollution index method can comprehensively evaluate the environmental quality of soil, not only reflecting the impact of various pollutants on the soil environment but also highlighting the role of high-concentration pollutants. At the same time, the pollution grade of soil environment quality can be determined according to the calculated Nemero pollution index. Therefore, this paper puts forward a modeling method of complex geological soil heavy metal evaluation based on the Nemerow index method. This paper analyzes the problem of complex geological SHMP from both theoretical and practical aspects, and introduces the Nemerow index method to ensure that the evaluation factors obtain reasonable scores, effectively correct the problems existing in the original method, and provide reference for the investigation of complex geological SHMP [8–10].

2. Materials and Methods

Before evaluating heavy metals in complex geological soils, an analysis of the current status and sources of SHMP (Soil Heavy Metal Pollution) is required. On the basis of previous studies, this study combines various index evaluation methods, ArcGIS technology, and a human health risk assessment to obtain the contents of Hg, As, Cd, Cr, Pb, and other heavy metals in the soil of the study area. We determine the spatial distribution and pollution accumulation statuses, discuss the pollution of soil heavy metals and analyze their pollution sources, and provide reference for the research of soil heavy metals.

2.1. Study Area

The selected area for the study was Lechang, a county-level city in Shaoguan, Guangdong Province, China. The observation data of the meteorological station shows that the average annual rainfall in this area is 1549 mm. The rainy season is from April to August, accounting for 75.3% of the annual rainfall. The average annual evaporation is 1652.7 mm, and the average annual temperature is 21.6 °C. The annual total solar radiation is 1.90×102 kJ/cm^2, and the average annual amount of sunshine hours is 1319.0 h, while the frost free period is 328 days [11].

The terrain in the region is mainly consistent with the trends of the northeast-southwest region with multiple fault zones, such as normal faults, reverse faults, and faults of an unknown nature. There are polymetallic mines along the fault zone, the broken zones and breccias on both sides of the fault are extremely developed, the metal content and heavy sand anomalies are distributed in long strips [12], more than 10 polymetallic mines have been found, and its resources, which are mainly mineral, include Pb, Cu, Zn, and Sb (Figure 1).

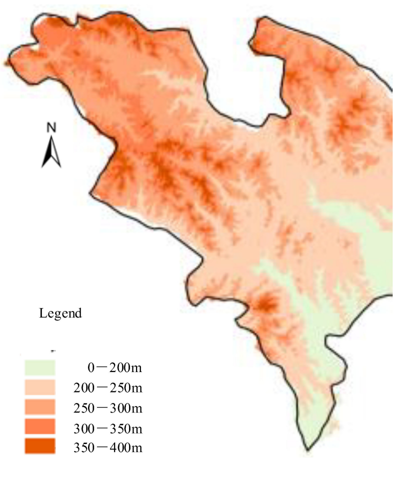

Figure 1. Spatial distribution map of soil erosion (M stands for meter).

2.2. Data Sources

At present, there is still a lack of publicly available soil heavy metal survey data in related fields, but there are many areas where SHMP monitoring and survey work has been completed, and relevant data and results have been published at home and abroad [13,14]. This study collected relevant data on heavy metal content in farmland soil in China from 2015 to 2019.

2.3. Sample Processing and Analysis

Taking into account the basic conditions of the study area, such as the monsoon wind direction, river trends, and geological characteristics, sampling points were arranged every 200 m in the east, west, and north directions. Soil samples were mainly farmland soil, which were collected and sealed in plastic bags. During the sampling process, the longitude and latitude of soil samples were recorded with a GPS positioning instrument, and the type, texture, and surrounding environment of the farmland soil for each sample were observed and recorded on the sampling registration form. The collected soil samples were placed in the room for natural air drying, the wooden rod was then used to break the larger soil block, and the sundries, such as gravel and dead branches, in the samples were removed manually. Then the samples were ground and passed through a 200 mesh sieve, 20 mesh sieve, and 10 mesh sieve. Finally, the samples were numbered, sealed, dried, and stored for standby. The soil samples were digested by an electric heating plate. Deionized water and a super pure reagent were used in the digestion process. At the same time, a soil standard sample (GSS-18), blank sample, and parallel sample were used for quality control in the experimental process. The recovery rate was between 95% and 105%. The content of heavy metals in the digested soil samples was determined by ICP-MS (Nexion 2000 B).

2.4. Research Methods

2.4.1. Single-Factor Evaluation

The single-factor method evaluates the cumulative pollution degree of heavy metal elements based on the background value of the soil elements. The expression is:

$$G_i = \frac{P_n}{c_s} \quad (1)$$

In the formula, G_i represents a SPI (Single pollution index); P_n denotes the actual content value of each heavy metal in mg/kg; c_s represents the background value of soil heavy metal in mg/kg. If $G_i \leq 1.0$, the soil is not artificially polluted; if the content of heavy metals exceeds the background value of the soil, it means that there is an accumulation of heavy metals.

Although the single-factor method can effectively judge the condition of soil heavy metals, it cannot reflect the overall condition of the soil [15]. Therefore, the CPI method was adopted to further study the problem of soil heavy metals. This method fully takes into account the influence of multiple pollution factors, reflects the overall level of heavy metals from soil through mathematical models, and obtains more objective evaluation results [16]. This method mainly realizes the evaluation of soil heavy metals by calculating the mean value of the standard index of all pollution factors. The specific formula is:

$$x(k) = \sum_{i=1}^{k} x_i(h) \times P_n \quad (2)$$

where $x(k)$ represents the CPI value; k represents the actual measured value of each pollution factor; $x_i(h)$ represents the classification limit of each pollution factor under the standard concentration.

After calculation using Formula (2), a comprehensive index result was obtained. As shown in Table 1, according to the calculation result, we determined the level of water pollution and the number of pollution factors that exceeded the standard value.

Table 1. Classification table of soil pollution degree of heavy metals.

$x(k)$	Number of Exceeding Standard Value	Level
>2.5	Most heavy metal pollution (HMP) factors exceed the standard	Very bad
2.0–2.5	Some HMP factors exceed the standard	Poor
1.5–2.0	Individual HMP factors exceed the standard	General
1.0–1.5	No more than two exceeded	Good
0.5–1.0	All HMP factors have not exceeded the standard	Fine
<0.5	All HMP factors have not exceeded the standard	Excellent

2.4.2. Geo-Accumulation Index Method

The GAI method reflects the pollution level of a single element [17]. The expression of the soil heavy metal accumulation index is shown in Formula (3):

$$IG = \log_2 \frac{p(x,y)}{p(x),p(y)} \tag{3}$$

where $p(x)$ represents the original pollution degree of the soil; $p(y)$ represents the pollution degree of heavy metals. According to the soil heavy metal accumulation index, SHMP is divided into 6 levels: $IG < 0$ is level 0; $0 < IG < 1$ is level 1; $1 < IG < 2$ is level 2; $2 < IG < 3$ is level 3; $3 < IG < 4$ is grade 4; $4 < IG < 5$ is grade 5; $5 < IG < 6$ is grade 6. Level 0 means no pollution; level 1 means between no pollution and moderate pollution; level 2 means moderate pollution; level 3 means between moderate pollution and heavy pollution; level 4 means heavy pollution; level 5 means between severe pollution and extreme pollution; level 6 means extreme pollution [18–21].

2.4.3. Potential Ecological Hazard Index

The PEH index method firstly measures the content of heavy metals in the soil, obtains the single pollution coefficient, and then introduces the toxicity response coefficient of heavy metals to obtain the single PEH coefficient [22]. Finally, it obtains the PEH index of heavy metals in the soil by weighting. The formula is as follows:

$$P_a = \sum_{i=1}^{L-1} P_b = 1 - \alpha_i \tag{4}$$

where P_a denotes the PEH coefficient; L represents the toxic reaction coefficient of pollutants; P_b represents the PEH index; α_i represents the pollution index of the pollutants [23].

According to the calculation results, the hazard level classification table is obtained, as shown in Table 2.

Table 2. Potential ecological risk hazard classification table.

Types	The Level of Danger			
	Mild	Severe	Strength	Extremely Strong
Potential ecological hazard coefficient P_a	<35	35–70	70–90	>200
Potential ecological hazard index P_b	<140	140–280	280–450	>700

2.5. Evaluation Modeling Method of Heavy Metals in Complex Geological Soil Based on Nemerow Index Method

Although the above evaluation method can realize the evaluation of SHMP, the calculation process is tedious and complicated. To further enhance the evaluation effect of SHMP, the Nemerow index method was used to construct a complex geological soil heavy metal evaluation model [24–28]. The Nemerow index method is simple in process and convenient to calculate. The method considers the maximum and average values of multiple factors, collects important factors in the soil, and calculates and analyzes which level it belongs to, referring to soil environmental quality standards. Generally speaking, this method has the advantages of simple mathematical description and convenient operation [29]. The Nemerow index method comprehensively considers the comprehensive effects of multiple pollution elements and is the most widely used comprehensive index method in evaluating SHMP.

2.5.1. Standard Nemerow Index

The Nemerow index method has been extensively applied in evaluating the pollution status of various fields. The calculation process of the Nemerow index takes into account the extreme value and highlights the contribution of the maximum value. The Nemerow index calculation method can comprehensively reflect the status of SHMP. The calculation formula is:

$$\partial_a = \delta_i^l \times T \tag{5}$$

$$\partial_b = a_k^l \delta_j^l + \frac{1}{N}\omega_{jk}^l \tag{6}$$

where δ_i^l denotes the actual measured value of the pollution factor; δ_j^l represents the standard value corresponding to the pollution factor; a_k^l represents the maximum value of the pollution index; N represents the largest item in the evaluation factor; ω_{jk}^l denotes the comprehensive value of the standard Nemerow index method.

The Nemerow index method especially considers the impact of the largest factor on the evaluation results. In addition, the Nemerow evaluation method also considers the contribution of the average value and its evaluation results for environmental factors, which makes the method more comprehensive and objective [30,31].

(1) When N > 1, the environmental quality cannot meet the requirements of the evaluation;
(2) When N = 1, the environmental quality is the evaluation value that meets the requirements;
(3) When N < 1, the environmental quality can meet the requirements of the evaluation.

The evaluation grade of heavy metals in soil by the Nemerow index method is shown in Table 3.

Table 3. Corresponding evaluation scores of evaluation index categories.

Grade	Nemerow Soil Pollution Index	Evaluation Grade
1	$p \leqq 00.7$	Cleaning (safety)
2	$0.7 < p \leqq 1.0$	Clean (warning line)
3	$1.0 < p \leqq 2.0$	Mild pollution
4	$2.0 < p \leqq 3.0$	Moderate pollution
5	$p > 3.0$	Severe pollution

2.5.2. Construction of Nemerow Index Evaluation Model

The detailed process of using the Nemerow index method to construct a SHMP degree evaluation model is carried out as follows:

(1) The number of input complex geological soil layers is $k = 1, 2, \cdots, n$, the data component description is $K = (K_1, K_2, \cdots, K_n)$, the number of hierarchical connections is D, and the connection weight coefficient is D_k.
(2) Iterate the standard Nemerow index. If the maximum number of iterations and the minimum evaluation error [20] are known, the value interval of D_k is $[-1, 1]$.
(3) Bring the data component K into Formula (7) to obtain the initial data of the SHMP diffusion level:

$$E_i = w_1 \sum_{i=1}^{K} \varphi_i(x, y) \tag{7}$$

In the formula, w_1 represents the overall situation of heavy metal pollution in the soil; φ_i represents the spread of heavy metal pollution in the upper soil.

(4) Obtain the initial data of the persistence degree of SHMP by Formula (8):

$$E_j = w_2 \sum_{i=1}^{K} g_i(x, y) \tag{8}$$

where w_2 denotes the standard limit of SHMP; g_i represents the multiple of the pollution factor exceeding the standard limit.

(5) Calculate the pollution persistence degree parameter according to Formula (9):

$$D(n) = \sum_{i=1}^{K} [d_i(n) \times h_i(n)] \tag{9}$$

where $d_i(n)$ denotes the pollutant persistence coefficient, and its value is 1; $h_i(n)$ represents the ranking of pollutant persistence. The ranking is obtained by calculating the persistence of each pollutant.

Based on the above analysis, a flow chart for constructing a SHMP assessment model is given, as shown in Figure 2.

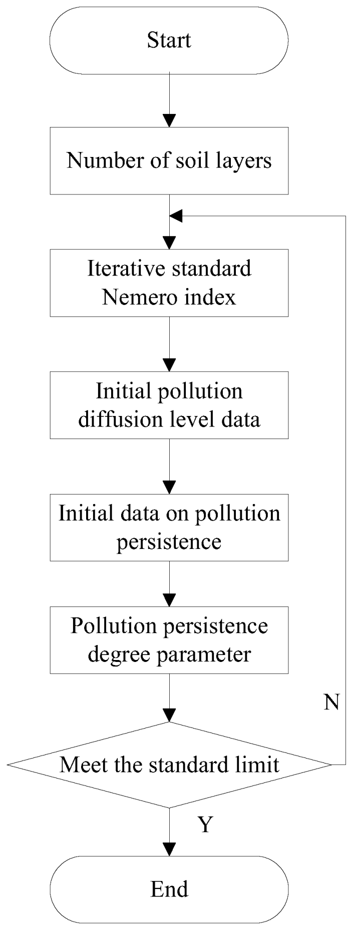

Figure 2. Flow chart of constructing the evaluation model of SHMP degree.

We used the constructed evaluation model to evaluate heavy metals in complex geological soils. The evaluation steps were as follows:

The classification of single components of soil environmental factors was divided, and the single group evaluation grade of the soil quality was obtained. The standard values of the measured values of each single index were compared. When each evaluation index was different from the standard value of the category, the category [32,33] of the detection index was determined according to the advantages rather than the disadvantages. The evaluation score of each category was determined according to the standard in Table 4.

Table 4. Corresponding evaluation scores of evaluation index categories.

Category	1	2	3	4	5
Points	0	3	6	9	12

According to Equation (10), we calculated the comprehensive score value calculated by the Nemerow index evaluation method:

$$F_{ij} = \frac{\sum_{i=1}^{K} [w_k \times (x_{ik} - v_{jk})]^2}{\sum_{i=1}^{K} [w_k \times (x_{ik} - v_{hk})]^2} \quad (10)$$

where w_k denotes the average value of a SPI; x_{ik} represents the largest SPI; v_{jk} represents the second largest SPI; v_{hk} represents the smallest SPI. When $F_{ij} \leq 0.9$, the soil is at a safe level and there is no pollution; when $0.6 < F_{ij} \leq 1.0$, the level of soil pollution needs attention; when $1.0 < F_{ij} \leq 1.5$, the soil pollution is at a light level; when $1.5 < F_{ij} \leq 2.0$, the soil pollution level has reached severe pollution [34,35].

According to the comprehensive score value, F_{ij} refers to the grading standard in Table 5 to determine the soil quality level.

Table 5. Soil quality classification.

Level	Heavy Pollution	Moderately Pollution	Light Pollution	Still Clean	Clean
F_{ij}	<0.3	0.3–0.6	0.6–0.73	0.73–0.82	0.82–1.0

3. Results and Analysis

To validate the evaluation modeling method for heavy metals in complex geological soils based on the Nemerow index method, experimental verification and analysis were carried out.

3.1. Evaluation of Individual Pollution Index

The Nemerow CPI method is combined with statistical analysis methods to evaluate the environmental quality of heavy metals in complex geological soils. According to the national "Soil Environmental Quality Standard (GB15618-1995)" level II standard, the SHMP status in the study area is analyzed.

It can be seen from Table 6 that the pollution degree of heavy metals is relatively low, and the clean areas of Hg, as, Cd, Cr and Pb are 896.2 km^2, 985.6 km^2, 1011.7 km^2, 1236.4 km^2 and 1307.1 km^2 respectively; The still clean areas of Hg, As, Cd, Cr, and Pb are 241.8 km^2, 30.2 km^2, 101.3 km^2, 3.69 km^2, and 0 km^2; the light pollution areas of Hg, As, Cd, Cr, and Pb are 5.29 km^2, 4.12 km^2 respectively, 8.52 km^2, 0.97 km^2, 0.15 km^2; The moderately pollution areas of Hg, As, Cd, Cr, and Pb were 1.23 km^2, 0 km^2, 10.29 km^2, 0 km^2, and 0 km^2, respectively; only As and Cd were heavy pollution, with areas of 1.20 km^2 and 7.63 km^2. At the same time, the pollution degree of Cd element in the study area is relatively high, reaching a severe pollution level, indicating that Cd has a large contribution to the comprehensive pollution of the study area and occupies the main component, while Pb element is in a low pollution state [36–38].

Table 6. Area statistics of soil environmental quality grade.

Pollution Level	Hg	As	Cd	Cr	Pb
$0.82 < F_{ij} < 1.0$	896.2	985.6	1011.7	1236.4	1307.1
$0.73 < F_{ij} < 0.82$	241.8	30.2	101.3	3.69	-
$0.6 < F_{ij} < 0.73$	5.29	4.12	8.52	0.97	0.15
$0.3 < F_{ij} < 0.6$	1.23	-	10.29	-	-
$F_{ij} < 0.3$	-	1.20	7.63	-	-

3.2. Comprehensive Evaluation of SHMP

SHMP is the result of multi-element comprehensive pollution. A SPI cannot completely and accurately reflect the degree of the comprehensive pollution of the soil environment by various heavy metal pollutants or highlight the impact of high-concentration pollutants. Therefore, the Nemerow CPI method was selected, and the national standard value was used as the evaluation standard to comprehensively evaluate the SHMP in the study area (Table 7).

Table 7. Comprehensive evaluation results of SHMP.

$x(k)$	Level	National Standard (km^2)	Research Area (km^2)
$x(k) > 2.5$	Very bad	0.83	16.80
$2.0 < x(k) < 2.5$	Poor	2.40	28.93
$1.5 < x(k) < 2.0$	General	12.40	1205.47
$1.0 < x(k) < 1.5$	Good	57.04	53.26
$0.5 < x(k) < 1.0$	Fine	157.97	0.12
$x(k) < 0.5$	Excellent	973.50	3.56

According to national standards, the SHMP in the study area was of a very poor level, but the proportion of it was relatively small. The pollution of the study area was mainly general and good, indicating that there was local light pollution in the studied area. From the perspective of the background value, the SHMP in the studied area was relatively heavy, and there was heavy pollution in the middle and northwest parts of the studied area, while 1205.47 km^2 was the general area of pollution in the studied area. It can be seen that, according to the national standards, the SHMP in the studied area was in a good condition. The reason for this phenomenon is that the standard limits of the background values of Hg (0.11 mg kg^{-1}) and Pb (35.2 mg kg^{-1}) in the studied area were far lower than the national standards of Hg (0.30 mg kg^{-1}) and Pb (250.0 mg kg^{-1}) [39].

3.3. Analysis of Soil Heavy Metals in Different Strata

The average content values of Hg, As, Cd, Cr, and Pb were 0.17 mg·kg^{-1}, 12.16 mg·kg^{-1}, 0.18 mg·kg^{-1}, 39.60 mg·kg^{-1}, and 80.01 mg·kg^{-1}, which are all lower than the national standard value. The average value of Hg and Pb exceeded the background value. The variances of the five soil heavy metals in descending order were 601.25 mg·kg^{-1}, 189.64 mg·kg^{-1}, 52.49 mg·kg^{-1}, 0.09 mg·kg^{-1}, and 0.03 mg·kg^{-1}, indicating Cr. The dispersion of Pb and As was much higher than that of Hg and Cd. The contents of Hg, As, Pb, Cr, and Cu all exceeded the standard, while the content of Cd did not (Table 8) [40].

Table 8. Statistics of detection values of heavy metals in shallow soil.

Classifications	Hg	As	Cd	Cr	Pb
Mean	0.17	12.16	0.18	39.60	80.01
Median	0.15	10.41	0.16	65.28	15.24
Standard deviation	0.05	7.28	0.04	14.08	10.13
Variance	0.03	52.49	0.09	601.25	189.64
Minimum	0.02	0.10	0.03	14.96	26.57
Maximum	0.37	87.45	1.89	752.12	253.6
Background value exceeding rate	0.15	1.25	-	6.38	71.25

The detection values of heavy metals in deep soil are shown in Table 9.

Table 9. Statistical table of detection values of heavy metals in deep soil.

Classifications	Hg	As	Cd	Cr	Pb
Mean	0.09	8.52	0.10	24.36	68.25
Median	0.07	8.54	0.11	52.39	12.02
Standard deviation	0.03	5.48	0.02	10.00	7.52
Variance	0.01	35.29	0.05	418.96	187.24
Minimum	0.01	0.05	0.01	9.28	10.89
Maximum	0.21	60.01	1.28	531.23	182.54
Background value exceeding rate	0.10	0.98	0.23	-	52.17

The average content values of Hg, As, Cd, Cr, and Pb were 0.09 mg·kg^{-1}, 8.52 mg·kg^{-1}, 0.10 mg·kg^{-1}, 24.36 mg·kg^{-1}, and 68.25 mg kg^{-1}, which are lower than the national standard value; the average value of Hg and Pb exceeded the background value. The variances of the five soil heavy metal contents in descending order were 418.96 mg·kg^{-1}, 187.24 mg·kg^{-1}, 35.29 mg·kg^{-1}, 0.05 mg·kg^{-1}, and 0.01 mg·kg^{-1}, indicating Cr. The dispersion of Pb and As was much higher than that of Hg and Cd. The contents of Hg, As, Pb, Cd, and Cu all exceeded the standard, except for Cr. From the results of Tables 7 and 8, it can be found that the content of heavy metals in the surface soil samples in the study area was higher than that in the deep soil. The reason is that the cohesive soil, with its high surface viscosity and poor permeability, had a good barrier effect. The concentration of metal elements in the surface layer was high, and the migration was very slow. The content of heavy metals had a significant downward trend with the increase of depth.

4. Conclusions

SHMP sources are complex, and there are many factors affecting the content of heavy metals in soil. Terrain, rivers, geological background, mines, factories and roads, and other human activities will also have a certain impact on SHMP levels. Based on the analysis of the CPI method, PEH index method, and GAI method, this study constructed a soil heavy metal assessment model based on the Nemerow index and conducted an experiment in Lechang City, Shaoguan, Guangdong Province. The results show that the evaluation model constructed could effectively evaluate the soil heavy metal pollution in the study area, which was highly consistent with the actual situation of the area. The model gave more accurate and reasonable evaluation results and achieved the purpose of evaluating and analyzing the heavy metal pollution level in the soil on a large spatial scale. However, this study only analyzed the spatial distribution of heavy metals in soil in a short amount of time. In order to conduct a comprehensive environmental quality assessment of soil quality, further dynamic monitoring is needed.

Author Contributions: J.W. proposed the research topic, investigated and sorted the literature, and obtained research funds; X.Z. designed the research program, investigated and collated the literature, conducted the statistical analysis, implemented the research process, designed the framework of the paper, and preformed the statistical analysis; J.L. collected and organized the data, drafted the paper, provided technical and material support, implemented the research process, revised the paper, and provided relevant suggestions; J.W., X.Z. and J.L. designed the research proposal, performed the final review of the paper, and extracted and discussed the conclusions. All authors have read and agreed to the published version of the manuscript.

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