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Research Article

Mechanism Analysis and Propagation Model of Heavy Metals Contamination in Urban Topsoil

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Abstract: In order to further research on the polluting condition and spreading features of heavy metals in urban surface soil, this study makes statistical analysis on indexes of 8 heavy metal concentrations. Then Are GIS geo-statistical analyst was used for Kriging interpolation of each kind of heavy metal concentration before figuring out the spatial distribution. Firstly, heavy metal contamination was analyzed by single-element pollution evaluation and multi-element pollution evaluation, before rationality analysis. Then, correlation extents between heavy polluting metals were calculated in each region by rationality analysis, leading to the correlations between the heavy metals. Finally, based on propagating features of different heavy metals, propagation models in water and atmosphere were established. Additionally, according to heavy metal distribution map, distribution point of high concentration was searched. With the assumption of the number of pollution source, theoretical concentration of sample point could be figured out, after the superposition of pollution intensity using propagation model based on data of the distribution points. Thus, the optimization model was established for locating the pollution source by minimizing the difference between theoretical value and actual value.

Keywords: Diffusion model, heavy metal contamination, kriging interpolation, pollution evaluation

INTRODUCTION

Heavy metal pollution means an environment pollution caused by heavy metals and its compound, which is one of the pollution doing great harm to human life (Liao *et al*., 2004). As pivotal component of urban ecosystem, urban soil plays a significant role in quality of inhabited environment and urban ecological function (Qian *et al*., 2011). However, the governance recovery difficulties are large since excess of heavy metals in soil would cause the destruction of ecosystem, leading indirect loss of crops (Loska *et al*., 2004).

At present, quantities of researches have been done on heavy metals in urban area. According to a research, a city with high influence intensity, long history and high industrialization and urbanization level suffers more heavy metal pollution (Chu and Zhu, 1994). Research of Bilos *et al*. (2001) shows that many heavy metal elements would be released to atmosphere if too many pollution sources gathering in a city. Meanwhile, Blake’s research shows that atmospheric deposition, including the absorption of gas-liquid suspension and precipitation, would lead to more heavy metal element in soil and crops (Blake and Goulding, 2002). According to research of Bandhu *et al*. (2000), close relationship was found between heavy metal contamination in atmosphere and that in soil. Moreover, heavy metal contamination in arterial road area is much higher than that in greenbelts according to Guan Dongsheng (Sutherland and Tolosa, 2000). Similar research was done by Kang Lingfen, who found that the heavy metal contamination in soil near main streets is higher than that in parks.

In this study, Kringing interpolation method and multi-element pollution evaluation model are used for spatial distribution of each kind of heavy metal before evaluating pollution level of heavy metals indifferent regions. Then, reasons of the heavy metal pollution are found based on correlation analysis. Finally, optimization model for locating the pollution source are established after building the propagation model under the condition of both atmosphere and water based on propagating features of heavy metal. The evaluation model and propagation models are meaningful for studying the evolution mode of urban geological environment.

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Table 1: Descriptive statistics of heavy mental content in soil/mg/kg

Element	Min.	Max.	Avg.	S.D.	C.V.	SLCOSOSE	Background value
As	1.61	11.680	5.420	2.520	46	25	3.600
Cd	0.04	1.620	0.280	0.200	72	0.6	0.130
Cr	15.12	258.150	46.440	24.710	53	250	31
Cu	2.29	248.850	39.760	36.800	92	100	13.200
Hg	0.00857	0.349	0.073	0.070	96	1.0	0.035
Ni	4.27	74.030	16.470	6.760	41	60	12.300
Pb	19.68	472.480	56.090	38.500	69	350	31
Zn	32.86	853.980	147.040	118.230	80	300	69

∗: Variation coefficient = (standard deviation/mean value) × 100%; SLCOSOSE: The second level criterion of standard of soil environment

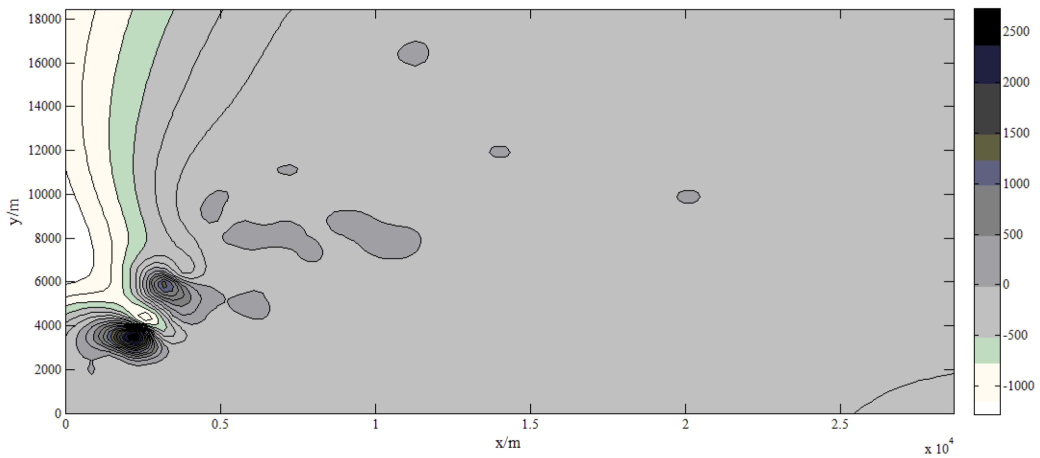

Fig. 1: Kriging interpolated distribution of Cu

SPATIAL DISTRIBUTION ANALYSIS OF HEAVY METALS BASED ON GIS THEORY

Soil quality of a city has been investigated. In the investigation, urban areas are divided into grids whose side length is 1kilometer. Then, record the location of sampling point by GPS, after sampling and numbering the surface soil, whose depth is 0~10 cm. There is only one sampling point in each of the grid. After that, concentrations of the 8 element contained in samples are measured. Moreover, soil in natural regions are sampled, whose elemental concentration is defined and calculated as background value of surface soil in the region according to data of sampling location, altitude and functional area the sampling location belongs to. Distance between every two sampling point is 2 km.

Descriptive statistics of heavy metal content in soil: After statistical processing on sample data, analysis result on heavy metal indexes, background value of the location and national standard value are figured out in the area, which is shown in Table 1.

According to Table 1, a larger variation coefficient means more unequal elemental distribution in soil, which results from human activities. Meanwhile, the maximums of all soil element contents are larger than the second grade standard of the national environmental quality standard for soil, leading to the conclusion that soil at sampling point has suffered effect by exogenous heavy mental due to human activities.

Interpolation for heavy metal content in soil: Based on *Kriging* interpolation using Are GIS Geostatistical Analyst, soil heavy mental distribution could be figured out. For example, Fig. 1 is the distribution of *Cu*.

According to Fig. 1, soil copper concentration, decreases from southwest, highest place in urban area, to northeast, which means a huge spatial differentiation. Distributions of other elements such as *Cr*, *Ni* and *Pb* are similar to that of *Cu* based on the results calculated. There are three high *Hg* concentration areas in south, southwest and central of the area, while concentration in other areas is low and asymmetrical. Distribution of *Cd* and *As* concentration is the same, whose scope is large. Concentration of the two elements is high in west, northeast and south of the area, leading to the result of little spatial differentiation. Meanwhile, concentration of *Zn* is centralized in the center of the area. The higher concentration in the west than that in the east lead to Spatial Differentiation between the east and the west.

EVALUATION MODEL FOR HEAVY METAL CONTAMINATION OF DIFFERENT REGIONS

Single-element-pollution evaluation method and Multi-element-pollution evaluation method were used in this study for analysis of heavy metal contamination in different regions. For characterizing the single element contamination, single-element exponential was used to calculate contamination of each heavy metal,

Table 2: Multi-element pollution comprehensive index of several types of regions

Sub-regions	Sub-region 1	Sub-region 2	Sub-region 3	Sub-region 4	Sub-region 5
Comprehensive index	1.02	2.08	0.12	1.33	0.66

Table 3: Pollution index of each heavy mental in five regions

	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Living area	0.12	0.34	0.010	0.41	0.060	0.12	0.12	0.72
Industrial area	0.17	0.55	0.020	1.32	0.630	0.16	0.19	0.90
Mountain area	0.02	0.04	0.001	0.04	0.006	0.07	0.02	0.01
Arterial road area	0.09	0.48	0.010	0.56	0.430	0.11	0.10	0.75
Greenbelts	0.12	0.32	0.010	0.20	0.080	0.06	0.09	0.36

resulting in the establishment of comprehensive index model. On combining the results of the eight heavy metals, contamination of different regions were figured out before rationality analysis.

Establishment of evaluation model for heavy mental contamination: The urban area was divided into five sub-regions, living area, industrial area, mountain area, arterial road area and greenbelts, based on different human influence on these areas. Thus, two kinds of methods were used for analyzing heavy metal contamination of each sub-region.

In the evaluation model, Formula (1) is the single-element-pollution evaluation:

$$I_i = \frac{C_i - B}{S_i - B} \quad (1)$$

where,

I_i = The sub-index of polluting Element i in sample
C_i = Real detection of Element i
S_i = Evaluation standard
B = Background value of Element *i*

Mean value of the same-element-sample sub-index was used representing polluting index of the area. Thus, the single-pollution comprehensive Index was figured out as Formula (2):

$$I = \frac{1}{n}\sum I_i \quad (2)$$

I is the comprehensive index of Element *i*, who contains *n* samples remaining counted in the sub-region.

Owing to the existence of several polluting elements in the same region, multi-element pollution evaluation was induced as Formula (3):

$$P = \frac{1}{2} \times \sqrt{(I_{ave}^2) + (I_{\max}^2)} \quad (3)$$

where,

P = Comprehensive index
I_{ave} = Mean value of element pollution index
I_{max} = The maximum of all element pollution index

Evaluation analysis of heavy mental contamination based on comprehensive index method: Value of multi-element pollution comprehensive index was figured out as following Table 2 after solving the heavy-metal-contamination evaluation model.

According to national scale of pollution, Sub-region 1 and 4 means slight pollution while Sub-region 2 means heavy pollution. Sub-region 3 means clean value while Sub-region 5 means alarm value. Comparing the value of comprehensive index with the scale of pollution, it could be pointed out that several heavy metals influence the environment in industrial area due to human life and traffic since there are not enough pollution prevention measures. Thus, it is suggested that well environmental condition ought to maintain by taking some preventive measures.

Eight heavy metal contaminations in 5 sub-regions were calculated according to the established single-element pollution evaluation model as is in Table 3.

According to Table 3, pollution index of *Zn* reaches 0.72 in industrial area, beyond the warning standard above, while that in other areas is much lower. In industrial area, pollution indexes of *Cd*, *Cu*, *Hg* and *Zn* are over the warning standard. For example, pollution index of *Cu* reaches 1.32, which threatens the environment around. Meanwhile, pollution indexes in mountain area are all below the warning standard. The element with the highest index is *Ni*, whose pollution value is 0.07, far from influencing the environment. Thus, it is supposed that there is little heavy metal pollution in the area. In arterial road area, pollution index of *Cu* and *Zn* are over the warning standard, which both become heavy polluting element. In greenbelts, polluting condition of the eight heavy metals is similar to mountain areas except the index of *Zn*, which have little side effect on environment.

Correlation analysis on heavy metals with high pollution level: According to the analysis above, industrial area and arterial area are the only two areas that over two heavy polluting elements exist. Hence, correlation analysis of heavy polluting elements was researched merely in industrial area.
Formula (4) is the correlation coefficient:

$$R = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2 \sum_{i=1}^{n}(Y_i - \overline{Y})^2}} \quad (4)$$

Table 4: Correlation coefficient between every two metals in industrial areas

	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
As	1							
Cd	0.32	1						
Cr	0.38	0.54	1					
Cu	0.15	0.56	0.91	1				
Hg	0.18	0.53	0.90	0.98	1			
Ni	0.68	0.48	0.69	0.50	0.47	1		
Pb	0.39	0.82	0.67	0.66	0.61	0.57	1	
Zn	0.51	0.75	0.69	0.62	0.59	0.63	0.73	1

Correlation coefficient of industrial and arterial areas could be calculated with Formula (4). The results are expressed in Table 4.

According to Table 4, correlation coefficient exists between *Cd*, *Cu*, *Hg* and *Zn,* the 4 heavy polluting metals. Correlation coefficient between *Cu* and *Hg* is 0.98, which is of a high level. The similar relationship exists between *Cd* and *Zn*, whose correlation relationship is 0.75, which means the two kinds of pollutions might come from a same pollution source.

PROPAGATION MODEL FOR HEAVY METAL POLLUTANT

Firstly, based on the propagation characteristic of each heavy metal element, different propagation models are established for the analysis of spatial distribution map of heavy metals. Then, number of pollution sources were assumed, before locating the pollution sources with sample value. Finally, by changing the number of pollution sources, comparison between theoretical value and actual value of samples were made, leading to location and number of the pollution source most proximate to actual value.

Propagation characteristic analysis for several heavy metal pollutants: In this area, diffusion mode of heavy metals differs from each other. Figure 2 is the conversion relationship between heavy metals.

According to Fig. 2, diffusion of heavy metals in urban area are mainly depend on factors, such as human flow, traffic, wind, rain and so on, leading to propagation and consolidation of heavy metals by water convection and atmosphere diffusion. According to China Environment, *Pb*, *Cd*, Cu and *Zn* could diffuse by both water convection and atmosphere diffusion while *As*, *Cr*, *Hg* and *Ni* could only diffuse by water convection.

Water transmission model for heavy metal pollutant: Compared to diffusion, transmission of heavy metal was supposed for neglect since it is by water transmission that heavy metals are mainly transferred in water. Based on one-dimensional water quality model, Formula (5) could be figured out:

$$\frac{\partial c}{\partial t} + u_x \frac{\partial c}{\partial x} = 0 \tag{5}$$

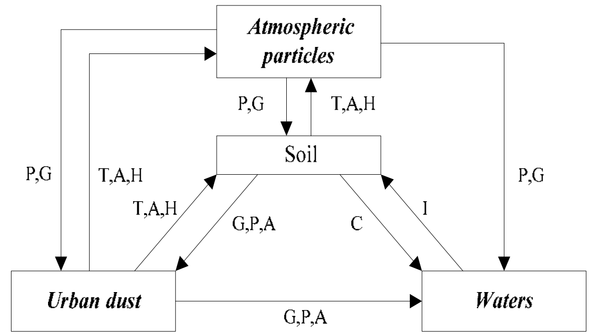

Fig. 2: Migration and transformation of heavy mental in urban environment
*: P-precipitation; G: Gravity sedimentation; A: Air transport; H: Human effects; T: Traffic flow; C: Chemosmotic precipitation; I: Irrigation

The following Formula (6) is two-dimensional water quality model:

$$\frac{\partial c}{\partial t} + u_x \frac{\partial c}{\partial x} + v_y \frac{\partial_c}{\partial_y} = 0 \tag{6}$$

Thus, the one-dimensional water quality model could be deducted, which is the water transmission model for heavy metal pollutant as Formula (7):

$$\frac{\partial c}{\partial t} + u_x \frac{\partial c}{\partial x} + v_y \frac{\partial_c}{\partial_y} + w_z \frac{\partial c}{\partial z} = 0 \tag{7}$$

c : The concentration
u_x, v_y, w_z : The transmission velocity in the direction of *x*, *y* and *z*

Atmosphere diffusion model for heavy metal pollutant: Since the elements, *Pb*, *Cd*, *Cu* and *Zn*, propagates not only by water but atmosphere. Moreover, without considering terrain and thermal effect, propagation of pollution are mainly determined by meteorological condition. Thus, pollutant diffusion model could be established based on mass conservation as Formula (8):

$$\frac{\partial c}{\partial t} + \bar{u}\frac{\partial c}{\partial x} + \bar{v}\frac{\partial c}{\partial y} + \bar{w}\frac{\partial c}{\partial z} = \frac{\partial}{\partial x}(K_x \frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial c}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial c}{\partial z}) + S \tag{8}$$

where,
c : The concentration of pollutant, kg/m^3
$\bar{u}$、$\bar{v}$、$\bar{w}$: Velocity component in direction of x, y and z
K_x, K_y, K_z : Turbulent diffusivity in direction of x, y and z
S : Source intensity of the pollution source

Table 5: Main-pollution-sources number and locations of eight heavy mental

Number	1	2	3
As	(13489, 3079, 0.6)	(18897, 10752, 0.3)	
Cd	(2374, 3056, 3.2)	(22479, 11732, 2.4)	(18034, 4089, 3.1)
Cr	(3761, 5744, 1.6)		
Cu	(2447, 3769, 0.1)		
Hg	(2892, 2553, 0.7)	(14327, 2355, 0.9)	(16482, 9045, 0.5)
Ni	(3634, 5822, 0.2)		
Pb	(2278, 3528, 1.2)	(5071, 5623, 0.9)	
Zn	(14223, 10065, 0.3)	(9566, 4951, 0.4)	

Moreover, the diffusion equation could be simplified as following under the condition of aerostatic stability.

Formula (9) is aerostatic stability:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}(K_x \frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial c}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial c}{\partial z}) + S \quad (9)$$

As a result, the atmosphere diffusion model for heavy metal pollutant under the stable time-invariant condition as Formula (10):

$$\frac{\partial}{\partial x}(K_x \frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial c}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial c}{\partial z}) + S = 0 \quad (10)$$

Optimization model for locations of pollution sources: Since the influence of pollution sources on arbitrary point is determined by pollution intensity and distance between the arbitrary point and pollution. By superposition the influence of pollution source, superposition equation was figured out as Formula (11):

$$C_{theory}^{(k)} = C_1(q_1, h_1^{(k)}) + C_2(q_2, h_2^{(k)}) + C_3(q_3, h_3^{(K)}) \quad (11)$$

$C^{(k)}_{theory}$: The theoretical concentration of heavy metals on k, the sample point

$C_i(q_1, h_1^{(k)})$: The propagation model for the l^{th} pollution source of heavy metals

q_l : The fixed pollution intensity of the l^{th} pollution source

h_l : The spatial distance between the sample point to the l^{th} pollution source

After analysis on the heavy mental distribution map, specific location of each pollution source is figured out with the assumptions that there are 3 pollution sources only. However, since the specific number of pollution source is uncertain, pollution source was added one by one until the number reaches the maximum that may exist in reality. Then, after the analysis of each kind of pollution source, square of the difference between theoretical value and actual value of each sample point is calculated. The number of pollution source is the minimal mean value of the square value. Thus, the optimization model is established as Formula (12):

$$Min \frac{1}{n} \sum_{k=1}^{n} (C_{theory}^{(k)} - C_{reality}^{(k)})^2$$

$$\begin{cases} h_l^{(k)} = \sqrt{(x_l - a_k)^2 + (y_l - b_k)^2 + (z_l + c_k)^2} \\ x_l \geq 0, y_l \geq 0, z_l \geq 0, q_l \geq 0 \\ l \leq n, l \subseteq N^* \\ k \leq n, k \subseteq N^* \end{cases} \quad (12)$$

where,

$C^{(k)}$: The actual concentration of heavy metals on k, the sample point

h_l : The spatial distance between the sample point to the l^{th} pollution source

a_k, b_k, c_k : The space coordinate value of sample value

n : The number of pollutant whose maximum is maximum permissible value of heavy metals according to heavy metal distribution map in the area

Calculating number and locations of pollution sources: According to optimization model established in 4.2, number and location of the eight-heavy-metal pollution source are figured out, which are shown in Table 5.

CONCLUSION

According to the statistical analysis on indexes of 8 heavy metal concentration, maximum, minimum and mean value of the heavy metal concentrations were characterized. Compared to element background value of the area, the effect and standard exceeding conditions are studied. By *Are GIS* Geo-statistical Analyst for *Kriging* interpolation of each kind of heavy metal concentrations, distribution maps of each kind of heavy metals are rendered before discussion of distribution of each kind of element. Upon analyzing contamination of different regions, single-element pollution evaluation method and multi-element pollution evaluation method were used. Heavy metal contaminations in different areas are figured out before rationality analysis. When analyzing the propagation features of heavy metals, it is found that propagation of heavy metals mainly depends on human flow, traffic, wind, rain and so on. Thus, the heavy-metal propagation model was established in water and atmosphere. Then, optimization model is established by comparing theoretical value, the pollution intensity superposition that the assumed pollution sources have on sample points and actual value. Location of the pollution source could be figured out by minimizing the deviation between theoretical value and actual value within the restrain range.

Heavy metal propagation model is well considered in this study, in which diffusion models were established instead of traditional models. Inverse source was used twice on calculating the pollution source, leading to a more accurate result. Due to shortcoming of the method, contaminations of pollution source influenced by time and topographic factor are ignored during calculation.

Hence, a three-dimensional model could be established for locating the pollution source, since the contamination and diffusion intensity of pollution source changes as time pass. Moreover, it is necessary to consider the influence of topographic factor since diffusion intensity results from different terrains. Thus, the equation would be of more accuracy by taking quantized topographic into consideration.

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