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Study on treatment effect assessment of heavy metal pollution in Taihu lake sediments based on the rapid development of Yangtze River delta urban agglomeration in China

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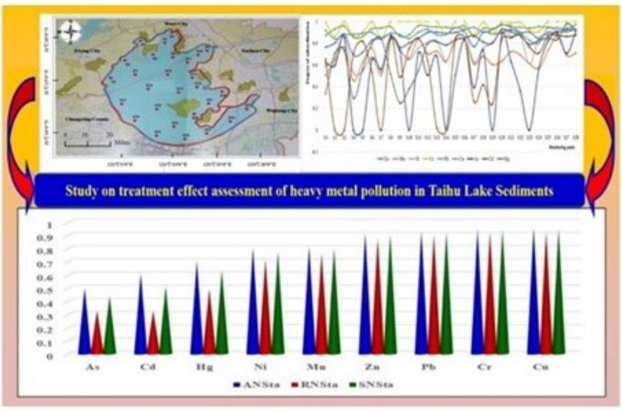
Graphical abstract



Abstract

In order to explore an effective assessment method for the treatment effect of heavy metal pollution in the sediment of Taihu Lake in China, based on the research background analysis and literature review, this paper reconstructs the spatial niche suitability model and applies it to the effect assessment of heavy metal pollution treatment in Taihu Lake sediment. The study found that the pollution degree of heavy metals in Taihu Lake sediment is as follows: North water area, West water area, South water area and East water area. The assessment results of the effect of heavy metal pollution treatment in Taihu Lake sediment by using SNSM are as follows: *As* > *Cd* > *Hg* > *Ni* > *Mn* > *Zn* > *Pb* > *Cr* > *Cu*. The four heavy metals that pose the greatest threat to the effect of Taihu Lake sediment are *As, Cd*, *Hg* and *Ni*; in particular, *As* and *Cd* are carcinogenic heavy metals, which the management authorities should pay special attention to. The research results of this paper are of great significance in supporting the government to formulate relevant policies for treating Taihu Lake and helping the management departments improve the treatment effect of heavy metal pollution in Taihu Lake sediments.

Keywords. Effect assessment, heavy metal pollution, Taihu Lake sediment, spatial niche suitability model

1. Introduction

Taihu Lake is China's third-largest freshwater lake and is located in the core area of the Yangtze River Delta, between Jiangsu and Zhejiang provinces. Through Taihu Lake, Yangtze River water flows into the East China Sea. The sediments at the bottom of Taihu Lake are gradually generated by the flow deposition of the Yangtze River, containing a large number of viruses, bacteria and harmful elements (Xue *et al.*, 2020; Yu *et al.*, 2021). In particular, the heavy metal pollution treatment in the sludge at the bottom of the lake poses a specific poison threat to the organisms and animals in the lake, the residents around Taihu Lake, people exposed to lake bottom sediments, and consumers of aquatic products (Cao *et al.*, 2018; Wu *et al.*, 2019; Wu *et al.*, 2020). As the water resources of the Yangtze River flow through Taihu Lake, the heavy metal pollutants in the sediments at the bottom of Taihu Lake will flow out of the lake area and cause pollution to the lower reaches of the Yangtze River (Ohore *et al.*, 2019; Niu *et al.*, 2020). The content of heavy metals in the sediment of Taihu Lake is an important indicator of lake water pollution, which reflects the water quality of Taihu Lake to a great extent (Ma *et al.*, 2015; Chen *et al.*, 2019). The potential effect of heavy metal pollution in Taihu Lake sediments directly or indirectly poses a significant threat to the quality of lake water, the surrounding ecological environment, and the health and even life of relevant people (Wu *et al.*, 2017; Liu *et al.*, 2020). According to the latest research results, the content of heavy metals in lake sediments is cumulative, and its concentration is dozens or even hundreds of times that of heavy metals in lake water (Wang *et al.*, 2020). As Taihu Lake is located in the core area of the Yangtze River Delta urban agglomeration, the heavy metals in the lake sediments are derived primarily from emissions from the consumption of petrochemical fuel for industrial production around Taihu Lake, exhaust emissions from motor vehicles passing through Taihu Lake, heavy metals in atmospheric sediments, and the accumulation of heavy metals in the water flow in the upper reaches of the Yangtze River (Ti *et al.*, 2018; Zhou *et al.*, 2020). According to the findings of Chinese researchers, over half of the total amount of harmful elements in the sediments of Taihu Lake are deposited from the atmosphere by precipitation; air deposition has become the principal method of heavy metal pollution treatment in Taihu Lake sediments (Duce *et al.*, 1991; Chen *et al.*, 2019; Zhang *et al.*, 2020).

The rapid economic development of cities around Taihu Lake has promoted the scale of petrochemical energy consumption (Jiao *et al.*, 2015; Yuan *et al.*, 2019; He *et al.*, 2020). With the rapid development of urban agglomeration in the Yangtze River Delta, the wastewater, waste gas, and waste residue discharged by energy consumption, as well as industrial wastewater from tanning, electroplating processing, papermaking, printing and dyeing, smelting, and chemical industry, have promoted the continuous increase of heavy metal content in the sediment of Taihu Lake (Qin *et al.*, 2012; Rajeshkumar *et al.*, 2018; Zhou *et al.*, 2021). Besides, the phenomenon of direct or indirect inflow of domestic wastewater from residents around Taihu Lake increases the pollution (Dong *et al.*, 2019). More importantly, these pollutants contain many heavy metals, significantly increasing the content and pollution degree of heavy metals in Taihu Lake (Wu *et al.*, 2020). Taihu Lake is the primary source of domestic water, agricultural irrigation, aquaculture, and industrial development in surrounding cities (Fang *et al.*, 2018; Xu *et al.*, 2021). Domestic and foreign experts and scholars have studied Taihu Lake and found that heavy metals in the sediment of Taihu Lake are significantly higher than the background value in the crust, which has specific biological toxicity and environmental pollution on Taihu Lake (Qin *et al.*, 2012; Xu *et al.*, 2020). With the deepening pollution degree of Taihu Lake, the issue of environmental pollution and its treatment effect assessment has been proposed and attracted increasing attention from people (Huang *et al.*, 2019).

Through the above literature review, it is evident that there are still many deficiencies in the academic research on the assessment of the treatment effect of heavy metal pollution in Taihu Lake, mainly because the research methods are predominantly traditional and there has been no introduction of new methods. There are few studies on the effect assessment combined with economic development and living conditions of residents around Taihu Lake, and existing study on the source of heavy gold in the sediment of Taihu Lake is insufficiently comprehensive. This paper constructs three niche suitability models, trying to solve the problem of potential effect assessment of heavy metal pollution treatment in the Taihu Lake water area to promote the sustainable development of Taihu Lake in China.

2. Materials and methods

2.1. Research areas

In this paper, Taihu Lake, also known as Zhenze, Juqu, Wuhu, or Lize in ancient times. It is located in the core area of the Yangtze River Delta Urban Agglomeration. It stretches across Jiangsu and Zhejiang provinces, closing to Wuxi in the north, Huzhou in the south, Yixing in the west, and Suzhou in the east. Taihu Lake area is 2427.8 square kilometers, sediment is 2338.1 square kilometers, and the total length of the lake shoreline is 393.2 kilometers (Zhang *et al.*, 2019). Taihu Lake is close to two prefecture-level cities in Jiangsu with a GDP of more than a trillion yuan, namely Suzhou and Wuxi. In 2020, the total GDP of the two cities was 3.2541 trillion yuan, the total GDP of cities surrounding Taihu Lake exceeded 5 trillion yuan, and the total number of urban residents around Taihu Lake exceeded 10 million (Zhang and Teng, 2020). Heavy metal pollution treatment in Taihu Lake affects the weather and air quality of cities around the lake and the residents' health to a great extent. Therefore, the effect of heavy metal pollution treatment in Taihu Lake is closely related to green economic development and the health status of surrounding urban residents.

2.2. Collection of heavy metal detection samples

Heavy metals are metals with a density greater than $4.5 g/cm^3$. According to the actual situation of Taihu Lake, a total of 9 harmful heavy metals such as *As, Zn, Mn, Cr, Cu, Ni, Pb*, *As, Cd,* and *Hg* are selected in this paper. Among them, *As*, a non-metal with comparable qualities to heavy metals, is classified as heavy metal under the Chinese government's standard for the treatment of heavy metal pollution. In order to study the problem of effect assessment from heavy metals pollution in Taihu Lake sediments, we set up a research group to investigate the heavy metals content in Taihu Lake sediment. The survey lasted one year, from June 2019 to June 2020. We also investigated the domestic and foreign research results of pollution and effect assessment of Taihu Lake sediment, visited, and consulted the experts of Taihu Lake research in Jiangsu universities and research institutions. The purpose of the field investigation is to obtain the basic data of the research. According to the survey results, we decided to obtain samples from Taihu Lake sediment to detect heavy metals content. On this basis, on-site sampling was conducted at 28 planned sampling points in Taihu Lake from June 5 to 15, 2020. The distribution of sampling points determined the sampling point of this harmful element according to the research scheme is shown in Figure 1.

Table 1. Statistical table of detection results of heavy metals in sediment samples of Taihu Lake（Unit: $mg\times kg^{-1}$）

Sample	Zn	Mn	Ni	Cr	Pb	Cu	As	Cd	Hg
S_1	128.2364	522.3626	90.8726	52.2718	53.2642	64.2437	18.2427	0.4128	1.0237
S_2	109.3863	396.2638	77.2738	98.6528	91.2835	41.2738	19.2428	1.0638	0.4936
S_3	68.9827	275.3812	38.3728	41.2738	72.2736	31.2725	10.2836	1.4168	0.4562
S_4	163.6713	568.3217	102.3826	99.6527	70.2837	71.3764	51.4628	0.3627	1.0827

S_5	149.8629	402.3715	99.2731	84.2716	66.2735	68.3728	49.8726	0.2639	0.6972
S_6	96.3847	283.4817	76.2638	51.2727	62.2745	40.2716	17.2837	0.5218	0.3628
S_7	89.2735	496.2717	106.6812	102.1724	90.2628	38.3815	20.3724	1.2427	0.3028
S_8	70.2738	198.2736	42.3726	32.1627	65.7234	33.2719	9.8726	0.2439	0.7626
S_9	128.2734	304.2713	62.3725	42.3816	71.3624	67.3826	14.2739	0.5628	1.1426
S_{10}	108.2736	370.2736	80.2637	31.9728	89.3216	62.3821	40.2638	0.3273	0.9628
S_{11}	87.2731	205.2618	60.2635	33.2817	61.6236	29.3729	15.2438	0.2389	0.7217
S_{12}	62.2635	332.2717	52.2267	45.2732	48.2631	32.2576	22.3824	0.4238	0.3639
S_{13}	60.2716	310.2715	48.3721	48.2836	73.2736	34.2738	16.2839	0.98237	0.3429
S_{14}	66.2716	401.2817	82.2817	92.2718	86.2537	35.8727	50.2837	1.1937	0.3856
S_{15}	61.4826	221.2742	42.2836	38.2625	40.5265	37.8937	22.3418	0.2519	0.3138
S_{16}	59.2731	215.2718	32.1726	34.2735	47.9826	31.2739	10.9827	0.2347	0.2927
S_{17}	125.2732	421.2715	84.2637	93.2735	39.3628	69.0245	26.3826	0.7628	0.2638
S_{18}	59.8726	356.2813	60.4216	52.3817	61.3824	39.48273	14.2739	0.6238	0.3459
S_{19}	68.2832	426.1728	51.2738	89.3281	49.2418	40.2348	45.5927	0.7838	0.3589
S_{20}	62.1725	397.7216	28.0217	51.2834	28.9725	25.4695	9.3728	0.2498	0.1836
S_{21}	48.9725	313.2738	40.2715	55.2136	32.6218	34.3624	17.9827	0.2358	0.2139
S_{22}	62.3826	342.2576	38.3814	53.2816	62.3862	35.2736	27.3847	0.2102	0.2638
S_{23}	60.2615	421.3863	87.2738	79.3523	98.2639	38.9328	51.2837	0.3128	0.3749
S_{24}	89.2638	458.2683	43.2714	83.2739	109.8763	33.2739	20.2817	0.3627	0.3249
S_{25}	61.2736	302.2863	38.2617	36.7823	38.2937	36.3827	11.2837	0.2182	0.2938
S_{26}	62.2739	180.2535	31.2618	32.2716	57.3827	37.2839	8.8376	0.2156	0.3128
S_{27}	50.1257	346.2768	26.4728	42.2718	58.2738	40.3827	15.2837	0.2238	0.1078
S_{28}	51.8926	328.2678	27.9815	30.2639	49.3726	26.0627	8.1629	0.2138	0.1924

Table 2. List of main statistical indicators of heavy metal data

Indicators	Zn	Mn	Ni	Cr	Pb	Cu	As	Cd	Hg
Minimum	48.973	180.254	26.473	30.264	28.973	25.470	8.163	0.210	0.108
Maximum	163.671	568.322	106.681	1.0.172	1.9.876	71.376	51.463	1.417	1.145
Mean	82.554	349.879	58.960	58.097	63.417	41.976	23.029	0.506	0.462
SD	31.806	98.576	25.088	24.740	20.433	14.033	14.356	0.363	0.289
CV	0.385	0.282	0.426	0.426	0.322	0.334	0.623	0.719	0.626

Table 3. Effect assessment standard for heavy metal pollution in the sediment of Taihu Lake

Pollution degree	Level I	Level II	Level III	Level IV	Level V
Zn	0-25	25-150	150-350	350-500	>500
Mn	0-100	100-200	200-300	300-500	>500
Ni	0-30	30-50	50-100	100-200	>200
Cr	0-60	60-90	90-210	210-300	>400
Pb	0-25	25-150	150-350	350-500	>500
Cu	0-30	30-120	120-280	280-400	>400
As	0-10	10-15	15-30	30-40	>40
Cd	0-0.20	0.20-0.30	0.30-0.60	0.6-1.00	>1.00
Hg	0-0.15	0.15-0.30	0.30-0.50	0.50-1.00	>1.50

Table 4. Normalized results of effect assessment indicators of heavy metal pollution treatment in Taihu Lake

Sample	Zn	Mn	Ni	Cr	Pb	Cu	As	Cd	Hg
S_1	0.8290	0.3035	0.6971	0.9129	0.9290	0.8929	0.6960	0.7248	0.5450
S_2	0.8542	0.4716	0.7424	0.8356	0.8783	0.9312	0.6793	0.2908	0.7806
S_3	0.9080	0.6328	0.8721	0.9312	0.9036	0.9479	0.8286	0.0555	0.7972
S_4	0.7818	0.2422	0.6587	0.8339	0.9063	0.8810	0.1423	0.7582	0.5188
S_5	0.8002	0.4635	0.6691	0.8595	0.9116	0.8860	0.1688	0.8241	0.6901
S_6	0.8715	0.6220	0.7458	0.9145	0.9170	0.9329	0.7119	0.6521	0.8388
S_7	0.8810	0.3383	0.6444	0.8297	0.8796	0.9360	0.6605	0.1715	0.8654
S_8	0.9063	0.7356	0.8588	0.9464	0.9124	0.9445	0.8355	0.8374	0.6611
S_9	0.8290	0.5943	0.7921	0.9294	0.9049	0.8877	0.7621	0.6248	0.4922
S_{10}	0.8556	0.5063	0.7325	0.9467	0.8809	0.8960	0.3289	0.7818	0.5721
S_{11}	0.8836	0.7263	0.7991	0.9445	0.9178	0.9510	0.7459	0.8407	0.6792
S_{12}	0.9170	0.5570	0.8259	0.9245	0.9356	0.9462	0.6270	0.7175	0.8383
S_{13}	0.9196	0.5863	0.8388	0.9195	0.9023	0.9429	0.7286	0.3451	0.8476
S_{14}	0.9116	0.4650	0.7257	0.8462	0.8850	0.9402	0.1619	0.2042	0.8286

S_{15}	0.9180	0.7050	0.8591	0.9362	0.9460	0.9368	0.6276	0.8321	0.8605
S_{16}	0.9210	0.7130	0.8928	0.9429	0.9360	0.9479	0.8170	0.8435	0.8699
S_{17}	0.8330	0.4383	0.7191	0.8445	0.9475	0.8850	0.5603	0.4915	0.8828
S_{18}	0.9202	0.5250	0.7986	0.9127	0.9182	0.9342	0.7621	0.5841	0.8463
S_{19}	0.9090	0.4318	0.8291	0.8511	0.9343	0.9329	0.2401	0.4775	0.8405
S_{20}	0.9171	0.4697	0.9066	0.9145	0.9614	0.9576	0.8438	0.8335	0.9184
S_{21}	0.9347	0.5823	0.8658	0.9080	0.9565	0.9427	0.7003	0.8428	0.9049
S_{22}	0.9168	0.5437	0.8721	0.9112	0.9168	0.9412	0.5436	0.8599	0.8828
S_{23}	0.9197	0.4382	0.7091	0.8677	0.8690	0.9351	0.1453	0.7915	0.8334
S_{24}	0.8810	0.3890	0.8558	0.8612	0.8535	0.9445	0.6620	0.7582	0.8556
S_{25}	0.9183	0.5970	0.8725	0.9387	0.9489	0.9394	0.8119	0.8545	0.8694
S_{26}	0.9170	0.7597	0.8958	0.9462	0.9235	0.9379	0.8527	0.8563	0.8610
S_{27}	0.9332	0.5383	0.9118	0.9295	0.9223	0.9327	0.7453	0.8508	0.9521
S_{28}	0.9308	0.5623	0.9067	0.9496	0.9342	0.9566	0.8640	0.8575	0.9145

Table 5. Assessment results of different niche suitability models

Evaluation Method	Zn	Mn	Ni	Cr	Pb	Cu	As	Cd	Hg
$ANS_{t\alpha}$	0.9148	0.8123	0.7987	0.9457	0.9296	0.9562	0.4975	0.6064	0.7028
Level	I	II	III	I	I	I	IV	III	III
$RNS_{t\alpha}$	0.8748	0.7580	0.7130	0.9234	0.9016	0.9253	0.3246	0.3253	0.4891
Level	II	III	III	I	I	I	V	V	IV
ξ	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
$SNS_{t\alpha}$	0.9008	0.7933	0.7687	0.9379	0.9198	0.9454	0.4370	0.5080	0.6280
Level	I	III	III	I	I	I	IV	IV	III

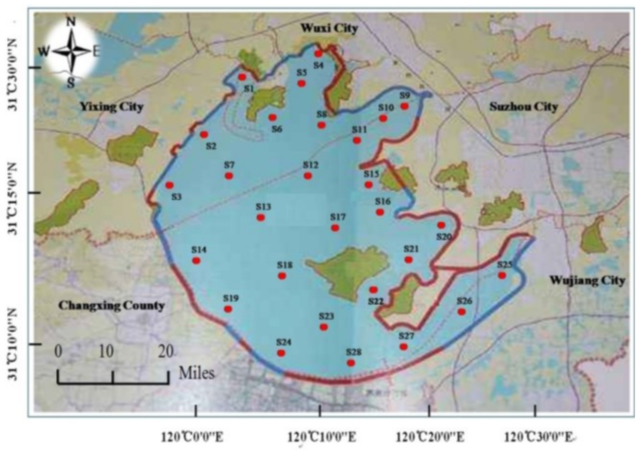


Figure 1. Cross section of sampling points for heavy metals detection in sediment of Taihu Lake

The sampling tools were a TC-600 gravity grab sediment sampler and GPS recorder, the water depth of the sampling point was 1-2m, and each sediment sample was 1-2L. The test sample is approximately 5-10cm above the bottom sediment sample; the test samples were packaged in plastic bags to minimize loss due to exposure to heavy metals in the sediment; The samples were subsequently provided to the laboratory personnel, who conducted standard detection on the sediment samples of Taihu Lake to obtain the basic data for this paper.

2.3. Detection of heavy metal concentration in sediment samples

In the laboratory, the stratified sample sediment was pretreated by microwave digestion, following which the frozen sample was dried and ground, and the sediment was dried, crushed, and well mixed Then, after screening with a 100-mesh nylon screen, take a 0.2-gram test sample, place it in a polytetrafluoroethylene microwave digestion tube, and add 6mL of nitric acid with a concentration of 65%-68%, 2mL of hydrofluoric acid with a concentration of 40%, and 1mL of perchloric acid with a concentration of 70%-72%. After using the microwave digestion instrument for degradation, place the sample on the heating plate for desilication, and stop adding the solution when the solution becomes viscous. After the solution has cooled, add 1mL of 1% nitric acid and 2mL of high-purity water before heating the tube to 100℃ and allowing it to reflux. The samples' content of *Zn, Mn, Cr, Cu, Ni, Pb, As, Cd,* and *Hg* was determined using an American Lee's man ICP-AES Prodigy XP full spectrum direct-reading emission spectrometer. The test error was less than 1%, and the professionals in the laboratory used professional instruments to measure and obtain the heavy metal test results of the test samples. After statistical analysis and a systematic classification of the test results, the test results of the heavy metal content for all samples are shown in Table 1.

Table 1 shows the basic data of heavy metals content in the sediment of Taihu Lake, which reflects the effect degree of heavy metal pollution in the sediment of Taihu Lake. The heavy metals content data measured in the experiment can clearly reflect the distribution of heavy metal content in Taihu Lake's sediment. These primary experimental data are arranged in the order of green to red according to the heavy metal content in Taihu Lake. The distributions are shown in Figure 2.

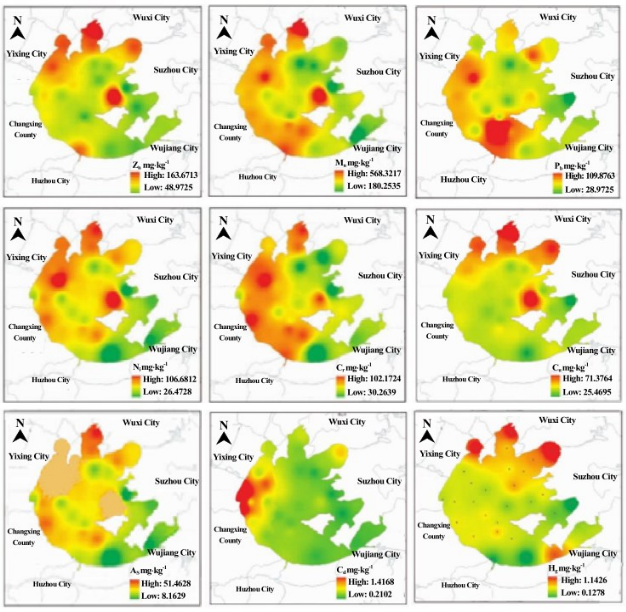


Figure 2. Distribution of heavy metals in sediment of Taihu Lake

According to the basic data in Table 1, the statistical analysis method is used to analyze the central characteristic values of the basic data, including the minimum value, maximum value, mean value, standard deviation, and coefficient of variation. The specific statistics of the heavy metal data are shown in Table 2.

In the above table, SD is the abbreviation of standard deviation; CV is the abbreviation of coefficient of variation. The content of heavy metals in Taihu Lake sediment can be used to compare the toxicity of the same harmful element. However, it cannot be used to compare the toxicity of different heavy metals. The comparison of toxicity between different heavy metals needs to be determined according to the assessment criteria and specific assessment results.

2.4. Construction of spatial niche suitability model

The effect assessment of heavy metal pollution treatment in the sediment of super-large lakes in the core area of urban agglomeration is a very important research topic. The degree of heavy metal pollution treatment directly determines the size of the effect (Wang *et al.*, 2020). According to the results of the literature review and the latest research results both domestically and abroad, the actual situation of Taihu Lake is fully considered, and the niche suitability model is constructed in order to explore the effective assessment methods of heavy metals pollution in the sediment of Taihu Lake and its therapeutic effect. A niche refers to the position of a population within the natural ecosystem in time and space, as well as its functional interaction with other populations in the environment that are unaffected by human activity. It represents the minimum habitat threshold necessary for the survival of each organism in the ecosystem. Suppose there are n ecological factors in a region, in that case, the quantized values of these ecological factors are expressed by X_i, the ecological factors matrix can be expressed as $X=\{X_1,X_2,\ldots,X_n\}$. The ecological factors of m regions can form (nXm) dimensional quantized values matrix of ecological factors (EFM), and the specific expression is as follows:

$$EFM=\begin{pmatrix} x_{1(t_1)} & x_{2(t_1)} & \cdots & x_{n(t_1)} \\ x_{1(t_2)} & x_{2(t_2)} & \cdots & x_{n(t_2)} \\ \vdots & \vdots & \vdots & \vdots \\ x_{1(t_m)} & x_{2(t_m)} & \cdots & x_n(t_m) \end{pmatrix} \quad (5)$$

In the above formula: i=1,2, ,n; j=1,2,…m, $x_i(t_j)$ is a subset of n-dimensional ecological factor space E^n at time t_j, then $f(x_1(t_j),x_2(t_j),\ldots,x_n(t_j))$ is called the niche of the ecosystem. Suppose the actual value of the ecological factor is $x_{t=}$, the most suitable value is $x_t=(x_1(t_j),x_2(t_j),\ldots,x_n(t_j))$, and the approach degree between the two is the niche suitability of ecological factors, expressed in NS_t. In that case, $NS_t=(x_i,x_\alpha)$,the niche suitability model can be determined by using the distance formula as follows:

$$\begin{aligned} NS_t &= \sum_{i=1}^{n} \frac{W_i(\delta_{\min}+\lambda\delta_{\max})}{\delta_{it}+\lambda\delta_{\max}} \\ &= \sum_{i=1}^{n} \frac{W_i\left\{\min\left[\left|x_i(t_j)-x_i(\alpha)\right|\right]+\max\lambda\left[\left|x_i(t_j)-x_i(\alpha)\right|\right]\right\}}{\left|x_i(t_j)-x_i(\alpha)\right|+\max\lambda\left\{\left|x_i(t_j)-x_i(\alpha)\right|\right\}} \end{aligned} \quad (6)$$

In the formula: $\delta_{it}=|x_i(t_j)-x_i(\alpha)|$, $\delta_{max}=max\{\delta_{it}\}=max\{|x_i(t_j)-x_i(\alpha)|\}$-, $\delta_{max}=max\{\delta_{it}\}=min\{|x_i(t_j)-x_i(\alpha)\}|$. i=1,2,…,m; t=1,2,…n; λ is the model parameter (0≤λ≤1), in the average case =0.5. In order to improve the effectiveness of niche suitability model assessment, this paper reconstructs the niche model based on the traditional niche suitability model and tries to build a comprehensive assessment model of spatial niche suitability. Taking the heavy metal concentration value in Taihu Lake as the niche value, $X_i(t_j)$ represents the concentration value of heavy metals at the ith detection point, the jth detection point. In order to construct the comprehensive assessment model of niche suitability, the generalized correlation degree in grey theory is introduced to calculate the niche of ecological factors (Ye *et al.*, 2016). Since the concentration of heavy metals in Taihu Lake sediment is obtained through a laboratory test, this paper does not adopt the weakening buffer processing of the assessment indicators. In order to facilitate the calculation of niche suitability, the assessment indicators need to be normalized processing, the data after normalization processing has no dimension, and its value range is between [0,1]. The specific calculation formula is as follows:

$$\begin{cases} X_i'(t_j)=X_i(t_j)\cdot\left[\max X_i(t_j)\right]^{-1} & \text{(forward pointer)} \\ X_i'(t_j)=1\text{-}X_i(t_j)\cdot\left[\max X_i(t_j)\right]^{-1} & \text{(contrary indicator)} \end{cases} \quad (7)$$

If $x_i(\alpha)$ is the most appropriate value in the assessment indicators in line i, $x_{i\alpha}$ is the most appropriate value after normalization processing. The specific calculation formula is as follows:

$$\begin{cases} X_i'(\alpha) = X_i(\alpha)\cdot\left[\max X_i(t_j)\right]^{-1} & \text{(forward pointer)} \\ X_i'(\alpha) = 1\text{-}X_i(\alpha)\cdot\left[\max X_i(t_j)\right]^{-1} & \text{(contrary indicator)} \end{cases} \quad (8)$$

In order to build a comprehensive assessment model of spatial niche suitability, firstly, an absolute niche suitability measurement model is constructed. According to the dimensionless processing results, use the following formula to calculate the absolute null transformation:

$$\begin{cases} X_{it}'(0) = \left(x_{1t}'(0), x_{2t}'(0), \cdots, x_{mt}(0)\right) = x_i'(t_j) - x_1'(t_j) \\ X_{i\alpha}'(0) = \left(x_{1\alpha}'(0), x_{2\alpha}'(0), \cdots, x_{m\alpha}'(0)\right) = x_i'(t_j) - x_1'(0) \end{cases} \quad (9)$$

Then, the absolute niche suitability model is constructed according to the results of absolute zero transformation and referring to the niche suitability basic model. The model is as follows:

$$ANS_{t\alpha} = \frac{1+|S_\alpha|+|S_t|}{1+|S_\alpha|+|S_t|+|S_\alpha - S_t|} \quad (10)$$

$$\begin{cases} S_t = \int_1^n \left(x_{it}'(0) - x_{i1}'(0)\right)dt \\ S_\alpha = \int_1^n \left(x_{i\alpha}'(0) - x_{i1}'(0)\right)dt \\ |S_t| = \left|\int_1^n \left(x_{it}'(0) - x_{i1}'(0)\right)dt\right| = \left|\sum_{k=2}^{n-1} x_{kt}'(0) + \frac{1}{2}x_{mt}'(0)\right| \\ |S_\alpha| = \left|\int_1^n \left(x_{i\alpha}'(0) - x_{i1}'(0)\right)dt\right| = \left|\sum_{k=2}^{n-1} x_{k\alpha}'(0) + \frac{1}{2}x_{mt}'(0)\right| \\ S_t - S_\alpha = \int_1^n \left(x_{it}'(0) - x_{i\alpha}'(0)\right)dt \\ |S_t - S_\alpha| = \left|\sum_{k=2}^{n-1}\left(x_{i\alpha}'(0) - x_{it}'(0)\right) + \frac{1}{2}\left(x_{m\alpha}'(0) - x_{kt}'(0)\right)\right| \end{cases}$$

On this basis, the relative niche suitability model is constructed by using the same method above. First, the relative null transformation calculation is carried out, and the calculation formula is as follows:

$$\begin{cases} X_{it}''(0) = \left(x_{1t}''(0), x_{2t}''(0), \cdots, x_{nt}''(0)\right) = x_i''(t_j) \times \left[x_1''(t_j)\right]^{-1} \\ X_{i\alpha}''(0) = \left(x_{1\alpha}''(0), x_{2\alpha}''(0), \cdots, x_{n\alpha}''(0)\right) = x_i''(\alpha) \times \left[x_1''(t_j)\right]^{-1} \end{cases} \quad (11)$$

Then, the relative niche suitability assessment model is constructed by using the above relative null transformation calculation results.The specific assessment model of relative niche suitability is as follows:

$$RNS_{t\alpha} = \frac{1+|S_\alpha''|+|S_t''|}{1+|S_\alpha''|+|S_t''|+|S_\alpha'' - S_t''|} \quad (12)$$

$$\begin{cases} S_t'' = \int_1^n \left(x_{it}''(0) - x_{i1}''(0)\right)dt \\ S_\alpha'' = \int_1^n \left(x_{i\alpha}''(0) - x_{i1}''(0)\right)dt \\ |S_t''| = \left|\int_1^n \left(x_{it}''(0) - x_{i1}''(0)\right)dt\right| = \left|\sum_{k=2}^{m-1} x_{kt}''(0) + \frac{1}{2}x_{mt}''(0)\right| \\ |S_\alpha''| = \left|\int_1^n \left(x_{i\alpha}''(0) - x_{i1}''(0)\right)dt\right| = \left|\sum_{k=2}^{m-1} x_{k\alpha}''(0) + \frac{1}{2}x_{m\alpha}''(0)\right| \\ S_t'' - S_\alpha'' = \int_1^n \left(x_{it}''(0) - x_{i\alpha}''(0)\right)dt \\ |S_t'' - S_\alpha''| = \left|\sum_{k=2}^{n-1}\left(x_{k\alpha}''(0) - x_{kt}''(0)\right) + \frac{1}{2}\left(x_{m\alpha}''(0) - x_{kt}''(0)\right)\right| \end{cases}$$

The comprehensive assessment model of spatial niche suitability is the weighted average value of the absolute and relative niche suitability models. If ξ is a relative weight, there are:

$$SNS_{t\alpha} = \xi \cdot ANS_{t\alpha} + (1-\xi)RNS_{t\alpha} \quad (13)$$

In the formula: $\xi \in [0,1]$ is the weighting coefficient. Considering that the importance of absolute and relative niche suitability is equal, the value of ξ is 0.5. When the value of $\xi$is less than 0.5 and tends to 0, the spatial niche suitability value tends to be the relative niche suitability value. When the value of W is greater than 0.5 and tends to 1, the spatial niche suitability value tends to be the absolute niche suitability value. In order to use the Spatial niche suitability model to assess the effect of heavy metals pollution in the sediment of Taihu Lake, based on the most recent Chinese and international research results (Wang *et al.*, 2019; Ohore *et al.*, 2019; Niu *et al.*, 2020), it is necessary to refer to *China's Urban Sewage Treatment Plant Sludge Quality* (GB T24188 -2009), *Urban Sewage Treatment Plant Sludge Treatment Technical Standard Consultation Draft* (*Jianbiao–gongzheng*[2017] No.149), *Urban Sewage Treatment Plant Pollutant Emission Standard* (GB18918-2016), and other statutory documents to determine the assessment standards for the potential effect levels of heavy metal pollution in the sediment of Taihu Lake, see Table 3.

Since the value range of the assessment result is within the interval [0, 1], the assessment results and the degree standards can be used to determine the potential effect level of heavy metals pollution in the sediment of Taihu Lake, as follows : Level I∈[0.90,1.00], excellent; Level II∈[0.80,0.90), good; Level III∈[0.60,0.80), medium; Level IV∈[0.40,0.60), pass; Level V∈[0,0.40), fail. In order to effectively assess the assessment objects, the value of a quantity of the assessment indicators must be standardized so that the value of the assessment indicators can be converted into comparable standardized values (Zhang *et al.*, 2017).

3. Results and discussion

3.1. Main research results

In order to use the spatial niche suitability model to assess the potential effect of heavy metal pollution in the sediment of the Taihu Lake, first use formula (7-8) to conduct a dimensionless process for the basic data in Table

1, where the maximum value is 1.5 times the lower boundary of level V and the assessment value of the indicator greater than this value is determined to be zero. The specific dimensionless processing results are shown in Table 4.

The absolute null transformation calculation is carried out based on the dimensionless treatment of the assessment indicators. First, absolute null transformation processing refers to the use of different methods to determine the zero base of the first row, that is, the data of each row of all assessment indicators minus the base data of the first row, so that the difference of the first row is zero. Then calculate the relative null transformation, which refers to the use of the ratio method to determine the zero base of the first row, that is, the ratio of the data in each row of all assessment indicators to the first row is used, and the ratio minus one is used as the calculation result; the data in the first row is zero. The author has utilized formulas (9) and (11) to calculate absolute and relative null transformation results for the assessment indicators. In the following, the author will use formulas (10), (12), and (13) to calculate the assessment results of the absolute niche suitability, the relative niche suitability, and the spatial niche suitability of the effect of heavy metal pollution treatment in Taihu Lake sediment, respectively. The composition, difference and trend of the assessment results obtained from the three assessment models are shown in Table 5.

According to the above assessment results, the assessment results using the absolute niche suitability model are: *Cu, Cr, Pb,* and *Zn* are Level I, its assessment result is excellent; *Mn* is Level II, its assessment result is good; *Ni, Hg,* and *Cd* are Level III, its assessment result is medium; *As* is Level IV, its assessment result is pass. The assessment results using the relative niche suitability model are: *Cu, Cr,* and *Pb* are Level I; *Zn* is Level II; *Mn* and *Ni* are Level III; *Hg* is Level IV; *Cd*and A_S are Level V. The assessment results using the spatial niche suitability model are: *Cu, Cr, Pb,* and *Zn* are Level I; *Mn, Ni,* and *Hg* are Level III; *Cd* and AS are Level IV.

3.2. Discussion on the assessment results and influencing factors

The above three niche suitability models are used to assess the effect of heavy metal pollution treatment in the sediment of Taihu Lake, and the assessment results are relatively different.

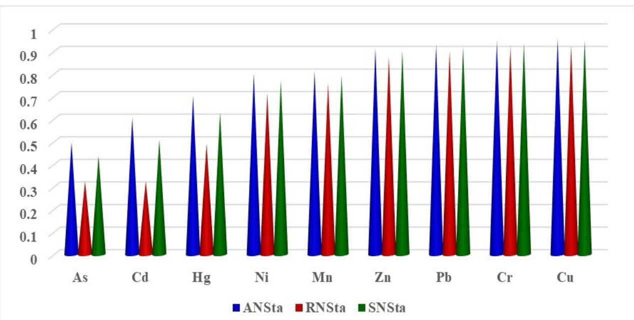


Figure 3. Difference of assessment results of different niche suitability models

In order to reflect the differences between the assessment results obtained by different assessment methods, the assessment results of the three niche suitability models are drawn with a cone diagram in the rectangular coordinate system, and the differences between them can be seen. See Figure 3 for the specific differences.

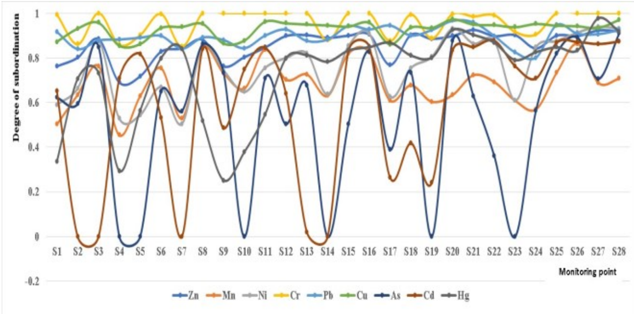


Figure 4. Variation diagram of main influencing factors of treatment effect of heavy metal pollution

It is evident from the above figure that the assessment result of the absolute niche suitability model is relatively high, the assessment result of the relative niche suitability model is relatively low, and the assessment result of the spatial niche suitability model is between the two. In addition to the impact of the assessment model on the assessment results, the basic data used in the assessment will also affect the assessment results to a certain extent. The main reason for the potential effect of Taihu Lake is the heavy metal content in the sediment. In order to reflect the distribution of the heavy metal content at 28 measuring points and its impact, the membership degree of heavy metal content indicators of all the samples in the sediment of Taihu Lake is plotted in a rectangular coordinate system. The specific content level, composition, and change rule of heavy metals are shown in Figure 4.

It can be seen from the above figure that the membership degree of heavy metals in Taihu Lake sediment is not the only factor determining the effect. The subordinate degree of certain heavy metals in the figure is extremely high, although it has little impact on potential effects, such as manganese. The subordinate degree of other heavy metals is not high, but it has a significant impact on potential effects, such as heavy metals *Cd*, *Hg*, and etc. In addition to the content of heavy metals, the factors affecting the potential effect of Taihu Lake also include the toxicity coefficients and assessment standards of heavy metals (Chen *et al.*, 2011).

3.3. Analysis of effect trend of heavy metal pollution treatment

According to the results of this study, the distribution of heavy metal pollution in Taihu Lake's sediment is relatively concentrated (Fang *et al.*, 2018). According to the spatial distribution of heavy metal pollution in the sediment of Taihu Lake, the effect in the east of Taihu Lake is the lowest, and the content of nine heavy metals in the sediment is relatively low, showing a good treatment effect. The main reason is that Suzhou is east of Taihu Lake, and Suzhou is the city with the best economic development in Jiangsu Province. The per capita GDP has reached 30000 US dollars, the investment in environmental pollution treatment is high, and the ecological environment is in good condition so that the ecological environment is the best. The western part of Taihu Lake is relatively serious in heavy metals pollution such as *Mn*, *Pb*, *Cr*, and A_s. The western part of Taihu Lake is Changxing County, where heavy metal emissions are concentrated due to the concentrated industry, the main reason is the lack of investment in environmental pollution treatment, and the potential effect is relatively large (Bian *et al.*, 2017). The northern part of Taihu Lake is the most heavily polluted area by heavy metals. The northern part of Taihu Lake is Wuxi that is one of the largest cities in Jiangsu Province and one of the cities with the fastest economic development, mainly due to the construction of Wuxi New District around Taihu Lake, where a large number of industrial clusters are concentrated around Taihu Lake and heavy metals pollution is inevitable. Wujiang City and Huzhou City are located south of Taihu Lake. The condition of economic development in these two cities is average. Around Taihu Lake, there are relatively few industrial firms, and heavy metal pollution levels are relatively low. The pollution of heavy metals such as A_s,C^d,H_g*and* N_i are relatively serious, caused by insufficient investment in environmental pollution treatment.

The excessive heavy metal content in the sediment of Taihu Lake is the main reason for the potential effect that is affected by many factors. Strengthening environmental pollution treatment is a critical way to reduce the potential effect of Taihu Lake (Sun *et al.*, 2020). According to the results of this study, heavy metals in the sediment of Taihu Lake are mainly related to the economic development of surrounding cities and the investment in environmental pollution treatment. Economic development is positively correlated with heavy metals' content, while investment in environmental pollution treatment is negatively correlated with the content of heavy metals. Maintaining the balance of the two relationships is the key to preventing effects in Taihu Lake. According to the detection results of heavy metals in the sediment of Taihu Lake and the niche suitability methods' assessment results, the pollution status of heavy metals in the sediment of Taihu Lake and the high potential effects are not formed in a short period. Therefore, the content of heavy metals in the sediment of Taihu Lake is rising, and the potential effect is also increasing. According to the evaluation results of the spatial ecological model, the effect of heavy metals *As* and *Cd* have reached level IV, and the effect of heavy metals H_g,N_i and M_n have reached level III. Dealing with the heavy metal pollution in Taihu Lake and promoting the continuous improvement of the governance effect have become an essential task for the surrounding units and the government, starting from two main aspects of pollutant emission reduction and environmental pollution treatment investment

4. Conclusion

The potential effect assessment of heavy metal pollution in the sediment of Taihu Lake is a critical research topic. To explore the effective assessment method of heavy metal pollution and its potential effect on the sediment of Taihu Lake, based on the literature review and research status analysis, nine heavy metals that have potential effects impacting Taihu Lake were selected according to the detection results. Moreover, after the technical processing of the assessment data, three niche suitability models, including the absolute niche suitability model, the relative niche suitability model, and the spatial niche suitability model, were constructed to assess the treatment effect of heavy metal pollution in Taihu Lake. The results showed that the heavy metal pollution in the sediment of Taihu Lake had reached a high level, the order of pollution degree are: *As> Cd > Hg >Ni >Mn>Zn >Pb >Cr >Cu.* The assessment results of the four heavy metal elements with serious pollution (*As >Cd >Hg >Ni*) are: level IV, level IV, level III and level III according to the spatial niche assessment model, among them, *As*and *Cd* are highly carcinogenic heavy metals. The study also found that the selection of assessment indicators and the construction of the assessment model are essential for assessing the treatment effect of heavy metal pollution in Taihu Lake. According to the research results of this paper, the government should make full use of the assessment results of the heavy metal pollution treatment, strengthen the treatment of *As*, *Cd*, and *Hg*, which are severely polluted, especially the treatment of the carcinogenic heavy metals *As* and *Cd*, promote the improvement of heavy metal pollution in Taihu Lake sediments, and continuously enhance the control effect. The treatment effect assessment of heavy metal pollution in the sediment of Taihu Lake is an important subject that needs long-term study. The purpose of this study is to promote the in-depth study of this subject in the academic community and to promote the continuous reduction of the degree of heavy metal pollution in Taihu Lake and the continuous improvement of the treatment effect of environmental pollution.

Abbreviation: HMP-heavy metal pollution; SNSM- spatial niche suitability model.

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