Pollution characteristics and risk assessment of surface sediments in nine plateau lakes of Yunnan Province

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Abstract. Sediment is the indicator of nutrient and heavy metal pollution in water environment, which can obviously reflect the pollution state in lakes. This paper reviews the literature of surface sediment pollution assessment of nine plateau lakes (Dianchi Lake, Erhai Lake, Fuxian Lake, Qilu Lake, Lugu Lake, Yangzonghai Lake, Yilong Lake, Xingyun Lake and Chenghai Lake) in Yunnan Province in the past ten years. TN (TN), total phosphorus (TP), copper (Cu), zinc (Zn), lead (Pb), chromium (Cr), cadmium (Cd), nickel (Ni), arsenic (As), mercury (Hg) are selected. As an evaluation index, the average contents in surface sediments of nine plateau lakes were 3517.53 mg/kg, 1826.86 mg/kg, 72.52 mg/kg, 215.43 mg/kg, 39.51 mg/kg, 69.66 mg/kg, 1.31 mg/kg, 43.83 mg/kg, 12.77 mg/kg and 0.21 mg/kg, respectively. Nutrient and heavy metals in sediments were evaluated by single pollution index method, ground accumulation index method and potential ecological risk index method. The results showed that nutrient pollution was serious, and the average pollution level was heavy pollution. Eight kinds of heavy metals were in moderate or below the pollution level. Cd and Hg were the main contributing factors in the ecological risk assessment of heavy metals. The correlation analysis shows that the TN pollution in surface sediments of nine plateau lakes is related to the average water depth, recharge coefficient and population density of the lakes.

1. Introduction
Depending on the results of the second Lake survey [1], there are 2693 natural lakes with a total area of 81414.6 km², accounting for about 0.9% of the national territory. There are many lakes and rivers in the province. The area of the lake reaches 1100 square kilometers, accounting for 0.28% of the total area of the province, and its total water storage is about 30 billion cubic meters. A total of more than 40 natural lakes, across the Yangtze River, the Pearl River, the Lancang River, the Salween River, the Daying river, Yuanjiang River six major river systems.

Sediments in lakes are habitats for many benthic organisms in aquatic ecosystems. Pollutants and pollutant elements are absorbed and collected in lake sediments through natural precipitation and surface sediment particulate matter. Under appropriate conditions, they are released through the sediment-water interface, causing secondary pollution to aquatic ecosystems. The main pollutants in lake sediments are heavy metals, nutrients and toxic and harmful substances. Eutrophication has traditionally been a prominent problem in freshwater lakes in China. Nitrogen and phosphorus in surface sediments of lakes occur in multiple forms. Through the geochemical process of sediment-water interface, the eutrophication degree and salinity of lakes are profoundly affected [2], which may...
lead to algae outbreak in lakes and affect the industrial, agricultural and domestic water needed for production and life. Some heavy metals, such as copper (Cu), zinc (Zn), lead (Pb), chromium (Cr), cadmium (Cd), nickel (Ni), arsenic (As) and mercury (Hg), enter rivers through rainfall, runoff and so on, and eventually enter the lakes. They are accumulated through the food chain and accumulated in organisms, and the risk of production is gradually expanded. Not only will it directly affect the safety of water environment, but it will also pose a threat to urban residents.

The study of modern lake sediments in China started relatively late. After 1970s, academic circles carried out systematic lake sediment studies. The main factors affecting the characteristics of lake sediments in China are: geological structure and topography of Lake areas, lake hydrological conditions (lake openness, wave and current), climate characteristics, lake water stratification, lake aquatic organisms and human dry activities [2]. Nine large plateau lakes (Dianchi Lake, Erhai Lake, Lugu Lake, Yangzonghai Lake, Yilong Lake, Xingyun Lake, Chenghai Lake) in the area are characterized by obvious landform characteristics, and lakes are all structural faulted freshwater lakes. At present, based on the investigation and analysis of the pollution characteristics of nine lakes in the nine provinces, the difference between 2-3 lakes is investigated and analyzed. Yu Zhenzhen et al [3] have studied the heavy metal pollution and potential ecological risk of surface sediments in Chenghai Lake. Chen Hong et al [4] by comparing the pollution of surface sediments in Chenghai Lake, Qilu Lake and the Lugu Lake, it was found that Qilu Lake was greatly affected by human and polluted more seriously. Dong Yunxian et al[5] according to the characteristics of Lake evolution, population density, dominant aquatic ecological function, eutrophication degree and water quality category, nine plateau lakes are divided into prevention, control and governance type from the perspective of ecological safety regulation. Most of the studies on plateau lakes by domestic scholars are based on the macro-analysis of the causes and the planning and management. They have not specifically analyzed the pollution characteristics and risk degree of the nine lakes, and calculated the correlation and influence the degree between the characteristics of the lakes and the pollution status quo. Therefore, the relevant parameters of nine plateau lakes in Yunnan Province, including water depth, climate, recharge coefficient, Lake opening stage, lake evolution stage, human disturbance and so on were statistically analyzed. The eutrophication degree, heavy metal pollution characteristics and risk level of surface sediments were analyzed, so as to preliminaries to analyze and summarize the reasons for the difference of plateau lake pollution in Yunnan province.

2. Materials and methods

2.1. Data sources and regional profiles

![Figure 1](image-url)  
**Figure 1.** Location of nine plateau lakes in Yunnan Province.
2.1.1. Data sources. Based on the published literature on lake sediments published by CNKI, VIP, web of science and other websites, we collected nearly seven years (2013-2019 years) of domestic scholars' investigation and study on the surface sediments of lakes in Yunnan Province, and selected nine plateau freshwater lakes as research objects. Except for the index content of Fuxian Lake and Xingyun Lake, the data of other plateau lakes are derived from nearly seven years' literature, and the distribution of lakes in the province is shown in Figure 1. Indicators of analysis and evaluation are divided into two parts: 1) heavy metal indicators, including Cu, Zn, Pb, Cr, Cd, Ni, As, Hg, mg/kg; 2) nutrient indicators, including TN, TP, mg/kg.

(1) Data determination of Fuxian Lake and Xingyun Lake
Sample collection and processing: according to the lake survey specifications, 8 sampling points are established in Fuxian Lake, numbered F1-F8 in sequence, and 6 sampling points are set in Xingyun Lake, numbered X1-X6 in sequence. The location distribution is illustrated in Figure 2 and Figure 3. The surface sediments (0-4cm) are collected at each sampling point in Peterson sampler. Three parallel samples are taken at each sampling point, mixed evenly, put into sealed pockets, and sealed and refrigerated after the air is removed. The experimental samples after freeze-drying in the laboratory are ground after impurities are removed. After passing 100 mesh nylon screens, they are placed in a desiccator for testing.

Sample determination method: TN and TP were determined by Alkaline sulfate combined digestion-Mo-Sb Anti spectrophotometric; Cu, Zn and Cr were determined by flame atomic absorption spectrophotometry; Pb, Cd and As were determined by inductively coupled plasma mass spectrometry; Hg was determined by cold atomic absorption spectrophotometry.

![Figure 2. Samples in Fuxian Lake.](image1)

![Figure 3. Samples in Xingyun Lake.](image2)

(2) Data collection of other plateau lakes
Recording the research data of the surface sediment of nine plateau lakes in Excel, including the content of heavy metals and nutrient elements in the surface sediment (0-4cm). Comparing the data of different articles, then choosing several groups of data which are close to each other in years and comprehensive data as the evaluation basis.

2.1.2. General situation. Yunnan province is located in the northwest border of China, north latitude 21° 8’ -29° 15’, east longitude 97° 31’ -106° 11’, the terrain shows high northwest and southeast low, and descends from north to south in step form. The eastern Yunnan and central Yunnan Plateau are part of the Yunnan-Guizhou Plateau. The western mountains and canyons are interglacial. They are mountain glacial landforms. Except for the plateau mountain climate in Northwest Yunnan, other parts of Yunnan belong to the subtropical and tropical monsoon climate.
The Dianchi Lake, Erhai Lake, Fuxian Lake, Qilu Lake, Lugu Lake, Yangzonghai Lake, Yilong Lake, Xingyun Lake and Chenghai Lake are known as nine large plateau lakes in Yunnan province. They mainly distribute in the northwest and Middle East of Yunnan province. The lakes are more than 30km² fresh water lakes. They mainly belong to the Yangtze River system, the Pearl River system and the Lancang river system. The main source of replenishment of the lake comes from the rainfall and surface of the lake. Replenishment of run off, Fuxian Lake, Qilu Lake and Yilong Lake receive groundwater recharge at the same time. Investigation lakes are structural lakes formed by water accumulation in depression basins caused by crustal tectonic movement. Specific causes include seismic fault subsidence, subsidence erosion, uplift of plateau, dissolution subsidence, graben fault depression, etc. The parameters of Lake weather, water depth and recharge coefficient are shown in Table 1.

**Table 1.** List of geological and hydrological characteristics of lakes in nine great plateaus.

| Lake Name   | Subordinate River System | Recharge Coefficient | Depth of Water | Population Density (People/km²) | Nutritional Status Index | Classification of Water Quality |
|-------------|--------------------------|----------------------|----------------|---------------------------------|--------------------------|---------------------------------|
| Dianchi     | Yangtze River            | 8.6                  | 2.93           | 1326                            | Eutrophic                | V                               |
| Erhai       | Lancang River            | 10.14                | 10.17          | 323                             | Medium                   | II                              |
| Fuxian      | Pearl River              | 5.14                 | 89.6           | 238                             | Oligotrophic             | I                               |
| Qilu        | Pearl River              | 9.25                 | 4.03           | 735                             | Eutrophic                | Inferior V                      |
| Lugu        | Yangtze River            | 3.54                 | 40.3           | 61                              | Oligotrophic             | I                               |
| Yangzonghai | Pearl River              | 6.1                  | 19.5           | 221                             | Medium                   | Inferior IV                     |
| Yilonghu    | Pearl River              | 13.5                 | 2.4            | 377                             | Medium                   | Inferior V                      |
| Xingyun     | Pearl River              | 10.9                 | 5.3            | 540                             | Medium                   | Inferior V                      |
| Chenghai    | Yangtze River            | 2.96                 | 25.7           | 104                             | Medium                   | IV                              |

2.2. **Nutrient evaluation method**

After nitrogen and phosphorus enter the lake, a considerable amount of nutrients for deposit in the mud, only a small part of which is absorbed by aquatic plants as nutrients. Waajen et al [6] believes that the eutrophication of lakes is closely related to the sediment of lakes. Studies show that the nitrogen and phosphorus in lake water may come mainly from the release of sediment when the external pollution of lakes is controlled[7].

At present, there is no unified evaluation method and standard for nutrient pollution in fresh water sediment at home and abroad. The statistical data are evaluated by a single factor index method, which includes TN and TP. The calculation method is shown in Formula 1, and the classification criterion of single factor pollution index is shown in Table 2. Machine hazard degree of main pollutants can be determined by single factor evaluation.

\[
P_i = \frac{C_i}{S_i}
\]  

where \( P_i \) is the pollution index of the element, \( C_i \) is the measured element content, \( S_i \) is the reference value of the element content, the evaluation reference values of TN and TP are 690 mg/kg and 543 mg/kg [8].
Table 2. Criteria for classification of nutrient single factor index in sediments.

| $P_i$ | $P_i \leq 1$ | $1 < P_i \leq 2$ | $2 < P_i \leq 3$ | $P_i > 3$ |
|-------|----------------|------------------|------------------|-----------|
| Pollution Level | None Pollution | Slight | Moderate | Heavy |

2.3. Evaluation method of heavy metals

Whether trace heavy metals, such as Cu, Fe, Zn, or non-essential heavy metals, are indispensable for normal physiological metabolism of organisms, their concentrations exceeding a certain threshold will cause toxicity or negative effects on the human body. In recent years, with the continuous improvement of human living standards and the rapid development of society (especially the rapid development of industrialization), there are a large number of heavy metals in the "three wastes" (waste gas, waste water, waste residue) produced by ore mining and smelting and production and life. Duan Zhi-bin et al. [9] showed that the characteristics of heavy metals, which are difficult to degrade and easy to enrich, will cause sustained damage to ecosystems over time.

Since the 1970s, numerous methods for evaluating heavy metals in surface sediments have emerged, such as the geo-accumulation index method, the sediment enrichment factor method, the sediment quality criteria method, the potential ecological risk index method, the multiple ecological risk index method, the regression overdose analysis method, etc. [9] Referring to the advantages and disadvantages of the existing evaluation methods, this paper adopts three commonly used methods of heavy metal evaluation, including the geo-accumulation index method, the potential ecological risk index method and the sediment quality index method.

2.3.1. The geo-accumulation index. The Geo-accumulation Index ($I_{geo}$) is used to evaluate and study the pollution degree of heavy metals in sediments and to classify the pollution degree of heavy metals. This method was proposed by Muller [10] in the 1960s and has been widely used in heavy metal pollution assessment since its establishment. The calculation method is shown in Formula 2.

$$ I_{geo} = \log_2\left(\frac{C_n}{1.5B_n}\right) $$

where $C_n$ is the concentration of the heavy metals in the environment, and $B_n$ is the concentration of heavy metals in the environmental background of this area. In this study, the environmental background values are the average values of the provinces in the national soil heavy metals census. Soil background values of the provinces and municipalities involved in this paper are shown in Table 3.

The criteria for evaluating the pollution grade of heavy metals in sediments by the geo-accumulative index method are shown in Table 4.

Table 3. A list of background values of heavy metals in soil and municipal soil.

| Provinces and cities | Cu  | Zn  | Pb  | Cr  | Cd  | Ni  | As  | Hg  |
|----------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Yunnan Province      | 46.3| 89.70| 40.60| 65.2| 0.218| 42.50| 18.4| 0.058|

Note: The Background Value of Chongqing Refers to that of Sichuan Province.

Table 4. Evaluation criteria for heavy metal pollution levels in sediments.

| Igeo | Igeo≤0 | 0<1Igeo≤1 | 1<1Igeo≤2 | 2<1Igeo≤3 | 3<1Igeo≤4 | 4<1Igeo≤5 | 5<1Igeo |
|------|--------|-----------|-----------|-----------|-----------|-----------|---------|
| Level| Clean  | Slight    | Partially moderate | Moderate | Partially serious | Serious | Severe |
2.3.2. The potential ecological risk. The Potential Ecological Risk is used to evaluate and classify the potential ecological risks of single elements and multiple elements in the sediment of lakes and reservoirs. The evaluation method was proposed by Hakanson[10]. Considering the concentration of heavy metals and the toxicity coefficient of heavy metals, the potential ecological risks of heavy metals are analysed and calculated. This method has been widely applied since it puts forward. For potential ecological risks of heavy metals, the calculation methods are shown in Formulas 3 and 4.

Single Heavy Metal Potential Risk Index:

\[ C_i^f = \frac{C_i}{C_i^f} \]

\[ E_i^f = T_i^f \times C_i^f \] (3)

Potential ecological risk index of multiple metals:

\[ R_i = \sum E_i^f = \sum T_i^f \frac{C_i}{C_i^f} \] (4)

Where \( C_i^f \) is a single pollutant pollution coefficient, \( C_i \) is the measured content of heavy metals in sediment, mg/kg, and \( C_i^f \) is a reference for the calculation, mg/kg. In this paper, the average of the provinces in the national soil heavy metal survey results are used. The background values of the provinces and cities involved in this paper are shown in Table 3.

\( E_i^f \) is the potential ecological risk coefficient of a single pollutant, and \( T_i^f \) is the toxicity response coefficient of a single pollutant. The toxicity response coefficients of Hg, Cd, As, Pb, Cu, Ni, Cr and Zn are 40, 30, 10, 5, 5, 5, 2 and 1, respectively.

\( R_i \) is a potential ecological risk index for many metals.

The application of the potential ecological risk index method for evaluating the potential ecological risk index of heavy metals in sediments is shown in Table 5.

| \( E_i^f \) | Level | \( 40 \leq E_i^f < 80 \) | \( 80 \leq E_i^f < 160 \) | \( 160 \leq E_i^f < 320 \) | \( 320 \leq E_i^f \) |
|------|------|-----------------|-----------------|-----------------|-----------------|
| Level | Low  | Moderate        | Considerable    | High            | Extremely High  |
| RI   | RI< 150 | 150<RI < 300     | 300<RI <600     | 600<RI<1200    | 1200<RI        |

3. Results and discussion

3.1. Statistical analysis of pollutant content in sediments

Among the nine plateau lakes, there are 8 lakes which are polluted by nutrients in surface sediments and 7 lakes which are polluted by heavy metals in surface sediments. The concentration values of the various elements are shown in Table 6. The results showed that the TN concentration values were: Xingyun Lake > Qilu Lake > Dianchi Lake > Yangzonghai Lake > Erhai Lake > Fuxian Lake > Lugu Lake. The minimum value is 1420 mg/kg and the maximum value is 5140 mg/kg.; the total phosphorus concentration values were: Xingyun Lake > Fuxian Lake > Dianchi Lake > Erhai Lake > Qilu Lake > Yangzonghai Lake> Lugu Lake, the minimum value was 670mg/kg, and the maximum value was 4790mg/kg. TN and TP mainly came from the use of agricultural fertilizer and the discharge of domestic sewage. The TN and TP concentrations in Lugu Lake were the lowest, which should be related to the population density of only 62 /km² in the basin and the low source of anthropogenic pollution.

According to the survey results, most of the researches on surface sediments of plateau nine lakes concentrated on heavy metals such as copper, zinc, lead and chromium, while the investigation of nickel and mercury was relatively few. The average contents of eight heavy metals in the investigated lakes were 72.5 mg/kg of Cu, 215.4 mg/kg of Zn, 39.5 mg/kg of Pb, 69.7 mg/kg of Cr, 1.3 mg/kg of Cd, 43.8 mg/kg of Ni, 12.8 mg/kg of As and 0.2 mg/kg of Hg. The highest values of Cu, Pb and Hg were found in the Dianchi Lake, 107.32mg/kg, 89.74mg/kg and 0.65mg/kg, respectively. The highest
values of Cr and Ni appeared in Yangzonghai Lake, 145.80mg/kg and 55.10mg/kg respectively, and the highest values of three heavy metals were zinc, cadmium and arsenic in Xingyun Lake, Fuxian Lake and Yilong lake. The Dianchi Lake located in the lower reaches of the city, it is the receiving water of industrial wastewater such as chemical industry, food, medicine and health, textile printing and dyeing, paper making, etc. Therefore, the concentration of heavy metals other than zinc is higher than the average value. There is no large industrial area near Lugu Lake and Chenghai Lake Basin, and the concentrations of heavy metals are below average.

### Table 6. A List of the concentration values of different elements in the surface sediments of the lake.

| Lake Name     | Nutrient | Heavy Metal (mg/kg) | Reference |
|---------------|----------|---------------------|-----------|
|               | TN       | TP                  | Cu  | Zn  | Pb  | Cr  | Cd  | Ni  | As  | Hg  |       |
| Dianchi       | 4487     | 1478                | 107 | 118.4 | 89.7 | 56.2 | 1.6 | -   | -   | 0.65 | [11,12] |
| Erhai         | 3538     | 1424                | -   | 111.4 | 89.7 | 56.2 | 1.6 | -   | -   | -    | [13,14] |
| Fuxian        | 1650     | 2245                | 74.4 | 277   | 10.4 | 39.6 | 1.8 | -   | 10.1 | 0.07 | Sampling |
| Qilu          | 4808     | 1030                | -   | -     | -    | -    | -   | -   | -   | -    |         |
| Lugu          | 1420     | 670                 | 59.2 | -     | 11.6 | 35.7 | -   | -   | -   | -    | [11,12] |
| Zongyanghai   | 3580     | 1151                | 97.6 | 149.2 | 40.3 | 145.8 | -  | 55.1 | 10.8 | -    | [9,16] |
| Yilong        | -        | 22.6                | 80   | 41.8 | 77.6 | 0.9  | 28.8 | 20.4 | -    | 10.5 | 0.1    | Sampling |
| Xingyun       | 5140     | 4790                | 90.4 | 559   | 54.7 | 63.1 | 1.7 | -   | 10.5 | 47.6 | 12.1   | 0.04   |
| Chenghai      | 56.2     | 109.0               | 28.1 | -     | -    | -    | 0.7 | 47.6 | 12.1 | 0.04 | [3]   |
| Average       | 3518     | 1940                | 72.5 | 215.4 | 39.5 | 69.7 | 1.3 | 43.8 | 12.8 | 0.2  |        |

### 3.2. Analysis and evaluation of nutrient content and pollution characteristics in sediments

#### 3.2.1. Analysis and evaluation of nutrient content in sediments. The background values of nutrient concentration were 690 mg/kg for TN and 543 mg/kg for TP, respectively. Compared with the TEC value (threshold effect content) and PEC value (possible effect content) determined by the Department of Environment and Energy of Ontario Province, Canada, [19], the background values of TN were higher than that of TEC value (550 mg/kg), and the background values of TP were slightly lower than that of TEC value (600 mg/kg), and the background values of both were much lower than those of PEC value (4800 mg/kg for TN). TP was 2000 mg/kg. Figure 4 shows the distribution of TN and TP in surface sediments of lakes. The results showed that the concentrations of TN and TP in the investigated lakes were higher than the background values, and the values of TN concentration varied greatly among the lakes. Overall, the content of nutrient elements in the investigated lakes is high.

![Figure 4](image-url)
3.2.2. **Analysis and evaluation of nutrient pollution characteristics in sediments.** The nutrient content in surface sediments of lakes was analyzed by single factor index method. The calculated results are shown in Table 7. The distribution of TN and TP in different pollution grades is shown in figure 5. The results showed that the average pollution index of TN and TP were 5.10 and 3.36 respectively, which belonged to heavy pollution level. There are only two lakes with moderate pollution of TN, and the rest are heavily polluted. TP pollution distributes evenly in all pollution levels, with three of them being heavily polluted and the remaining five being moderately and slightly polluted. Although the average pollution degree of TN and TP belongs to heavy pollution, the average value of a single pollution index and the distribution of lakes in different pollution levels show that TN pollution is more serious.

|       | Dianchi | Erhai  | Fuxian | Qiul  | Lugu  | Yangzonghai | Xingyun | Average |
|-------|---------|--------|--------|-------|-------|-------------|---------|---------|
| TN    | 6.50    | 5.13   | 2.39   | 6.97  | 2.06  | 5.19        | 7.45    | 5.10    |
| Level | Heavy   | Heavy  | Moderate| Heavy | Moderate| Heavy      | Heavy   | Heavy   |
| TP    | 2.72    | 2.62   | 4.13   | 1.90  | 1.23  | 2.12        | 8.82    | 3.36    |
| Level | Moderate| Moderate| Heavy | Slight| Slight| Moderate    | Heavy   | Heavy   |

**Figure 5.** Nutritional nutrient single factor index distribution map.

3.2.3. **Analysis of nutrient influencing factor.** The statistical method to study the correlation between variables is the correlation analysis method. The correlation analysis method is the uncertain relationship between variables. Common correlation coefficients is Pearson correlation coefficient, Spearman correlation coefficient and Kendall correlation coefficient. The range of correlation coefficients ranges from -1 to 1. The greater the absolute the value, the stronger the correlation between variables. The sign of the value represents the direction of correlation between variables. The sign of value represents the positive correlation between variables, and the sign of negative represents the negative correlation between variables. If the linear correlation coefficient is zero, it shows that there is no linear correlation between random variables. The corresponding range of Pearson correlation coefficient method is shown in Table 8.

| Absolute Range | 0 ≤ r ≤ 0.2 | 0.2 < r ≤ 0.4 | 0.4 < r ≤ 0.6 | 0.6 < r ≤ 0.8 | 0.8 < r ≤ 1 |
|----------------|-------------|----------------|----------------|----------------|-------------|
| Relevance      | Weak or Unrelated | Weak         | Moderate       | Strong        | Strong       |
Relevance analysis was made between the three parameters of recharge coefficient, average water depth and population density and the single factor pollution index representing the level of TN and TP pollution. The results are shown in Table 9. Pearson correlation coefficients of TN single factor pollution index Si to recharge coefficient, average water depth and population density were 0.87745, -0.83503 and 0.67031, respectively, with strong positive correlation, strong negative correlation and strong positive correlation. This indicates that with the decrease of average water depth, the increase of recharge coefficient or the increase of population density, the pollution degree of nutrients in surface sediments of investigated lakes will increase to varying degrees. Population density can indirectly express the degree of human disturbance. The greater the population density of lakes is, the greater the possibility of human disturbance. More agricultural production activities surrounding the lake area, the more serious the TN source pollution. At the same time, with the increase of recharge coefficient, non-point source pollution enters the lake and deposits at the bottom of the lake, which affects the TN content of surface sediments.

### Table 9. Correlation analysis table of nutrient pollution index and lake characteristics of surface sediments in lakes.

|                  | Si<sub>TN</sub> | Si<sub>TP</sub> | Recharge Coefficient | Mean Depth (m) | Population Density (people/km²) |
|------------------|-----------------|-----------------|----------------------|----------------|---------------------------------|
| Si<sub>TN</sub> | 1               |                 |                      |                |                                 |
| Si<sub>TP</sub> | 0.40689         | 1               |                      |                |                                 |
| Recharge Coefficient | 0.87745         | 0.50917         | 1                    |                |                                 |
| Depth of Water (m) | -0.83503        | -0.05668        | -0.71107             | 1              |                                 |
| Population Density (people/km²) | 0.67031         | 0.08374         | 0.52537              | -0.53395       | 1                               |

3.3. Characteristics of heavy metal pollution in sediments and assessment of ecological risk

3.3.1. Analysis and evaluation of heavy metal pollution characteristics in sediments. The results of the cumulative index of heavy metals in lakes (see Table 10) show that the most serious pollution phenomenon is Cd. The cumulative index values of Cd in lakes investigated are 2.25, 2.47, 1.38, 2.34 and 1.06, with an average value of 1.9, which are all at partially moderate or above pollution level. According to the soil background map of Cd concentration in The atlas of soil environmental background value in the people`s republic of China [20], the soil background value of the northwest and central Yunnan province ranges from 0.270 to 2.00mg/kg, which belong to the high background value area. It is speculated that the higher Cd concentration in the lake sediments of Yunnan province may be related to the high background value of the province. The heavy metals related to the high regional background values are also Cu. Background values of Cu ranged from 44.8 mg/kg to 250.00 mg/kg.

According to the evaluation criteria of local cumulative index (Table 4), the pollution level of the investigated lakes is classified. The proportion of different pollution levels of heavy metals is shown in Figure 6. The broken line part of the figure is the average pollution level of heavy metals. Figure 7 shows the proportion of heavy metal pollution levels in the investigated elements in each lake.

The average pollution level of heavy metals in the lakes was partially moderate and below. Among them, Zn, Pb, Cr, Ni and As were all in clean level, Cu and Hg were in slight pollution, and Cd pollution was close to moderate pollution. Figure 6 shows that although the proportion of heavy metal elements in different pollution levels is obviously different, the pollution degree of eight heavy metal elements is lower than that of partially moderate pollution, which belongs to moderate pollution, partially moderate pollution, slight pollution or clean. The highest proportion of moderately polluted elements is Cd, 60% of the investigated lakes are moderately polluted, and the remaining 40% are
partially moderately polluted. Secondly, Cu and Hg are moderately polluted in varying degrees, and the proportion of clean lakes is less than 50%. Ni and As are both clean in the investigated lakes. The order of pollution degree of heavy metals in the investigated lakes is Cd > Cu, Hg > Zn > Pb, Cr > Ni & As.

According to figure 7, we can draw the following conclusions: the heavy metal pollution level is the highest, 33% of the heavy metals are moderately polluted, 33% of the heavy metals belong to the slight pollution level, only 33% belong to the clean level. Next is Xingyun Lake. Since 1953, industry and agriculture in Xingyun Lake basin have developed rapidly and there are many pollution sources. Early data show that there are many pollution sources near the lake area, such as coal mines, phosphate mines, cement plants, aluminum products factories, packing plants and so on. Among the seven heavy metals pollution assessment in Xingyun Lake, only Pb, Cr and As are clean, Cu, Zn and Hg are clean and Cd is moderately polluted. The order of heavy metal pollution in lakes is: Dianchi Lake > Xingyun Lake > Yangzonghai Lake > Chenghai Lake > Fuxian Lake > Yilong Lake > Lugu Lake.

Table 10. Calculation results of accumulation index of different heavy metals in urban lake accumulation.

| Lake Name  | Cu  | Zn  | Pb  | Cr  | Cd  | Ni  | As  | Hg  |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Dianchi    | -0.02 | 0.63 | 0.56 | -0.80 | 2.25 | -  | -   | 2.91|
| Fuxian     | -2.04 | 0.10 | -2.55 | -1.30 | 2.47 | -  | -1.46 | -   |
| Lugu       | -0.44 | -0.23 | -2.40 | -1.45 | -   | -  | -   | -   |
| Yangzonghai| 1.34  | 0.49 | -0.60 | 0.58  | -   | -0.21 | -1.35 | -   |
| Yilong     | 0.38  | -1.62 | -0.54 | -0.33 | 1.38 | -1.15 | -0.44 | -   |
| Xingyun    | 0.84  | 0.38 | -0.15 | -0.63 | 2.34 | -1.39 | 0.13 | -   |
| Chenghai   | 2.28  | -0.31 | -1.12 | -   | 1.06 | -0.42 | -1.19 | -1.05|
| Average    | 0.33  | -0.08 | -0.97 | -0.66 | 1.9  | -0.59 | -1.17 | 0.66|

3.3.2. Potential ecological risk assessment of heavy metals in sediments. Potential risk index mainly reflects the toxicity level of heavy metals and the sensitivity of organisms to heavy metal pollution. The results of potential risk index calculation of heavy metal elements in surface sediments of lakes are shown in Table 11. The following conclusions can be drawn:

(1) The highest value of heavy metal comprehensive risk index RI in lakes was found at 688.73, which was at a high level of risk according to the risk assessment level of heavy metals. Secondly, Xingyun Lake, RI value was 322.95, at a considerable risk level; the lowest value appeared at RI; the lowest value was 8.9, and it was at a low risk level. On the whole, the comprehensive potential ecological risk level of the lakes surveyed is basically consistent with the pollution assessment results.
of the accumulative index of the base areas. The pollution level and potential ecological risk level of lake and Xingyun Lake were high, and the level of pollution and potential ecological risk were lowest.

(2) Because the heavy metal comprehensive risk index comes from the superposition of the single factor risk index, the Dianchi Lake and Xingyun Lake with high comprehensive risk index are analyzed. It was found that the higher comprehensive risk index was mainly due to Cd and Hg. Lugu Lake and Yangzonghai Lake did not carry out the investigation and evaluation of Cd and Hg. Their potential ecological risk indexes were 8.90 and 33.99 respectively. It can be concluded that Hg and Cd are the main contributors to the comprehensive potential ecological risk assessment of heavy metals in surface sediments.

(3) The highest potential ecological risk index of heavy metals is the Hg potential risk index of 449.57, and the risk level is extremely high. The risk level of Cd in lakes was high or considerable, and 58.3% of the lakes were at high risk level of Cd. According to the average ecological risk index, the order of potential ecological risk grade of eight heavy metal elements from high to low is Cd > Hg > Cu > As > Pb > Ni > Cr > Zn.

### Table 11. Calculation results of potential risk index of heavy metal elements.

| Lake Name     | Cu   | Zn  | Pb  | Cr  | Cd   | Ni | As  | Hg    | RI      |
|---------------|------|-----|-----|-----|------|----|-----|-------|---------|
| Dianchi       | 11.5 | 1.32| 11.0| 1.72| 213.47| -  | -   | 449.57| 688.73  |
| Fuxian        | 8.03 | 3.09| 1.28| 1.21| 249.08| -  | 5.46| -     | 268.16  |
| Lugu          | 6.39 | -   | 1.42| 1.09| -    | -  | -   | -     | 8.90    |
| Yangzonghai   | 10.5 | 1.66| 4.96| 4.47| -    | 6.48| 5.87| -     | 33.99   |
| Yilong        | 2.44 | 0.89| 5.15| 2.38| 116.97| 3.39| 11.0| -     | 142.31  |
| Xingyun       | 9.76 | 6.23| 6.74| 1.94| 227.06| 5.71| 65.52| -     | 322.95  |
| Chenghai      | 6.07 | 1.22| 3.46| -   | 93.58| 5.60| 6.58| 28.97 | 145.46  |
| Average       | 7.83 | 2.06| 4.87| 2.14| 180.03| 5.16| 6.94| 181.35| 230.07  |

### 4. Conclusions

Based on the evaluation of pollution characteristics and risk levels of nutrients and heavy metals in surface sediments of nine plateau freshwater lakes in Yunnan Province, the following conclusions are drawn:

(1) The level of nutrient pollution is higher, and TN pollution is more serious than total phosphorus pollution. The average pollution indices of TN and total phosphorus in surface sediments of lakes were 5.10 and 3.36 respectively, which belonged to heavy pollution level. TN in Qilu Lake, Xingyun Lake, Dianchi lake, Yangzonghai Lake and surface sediments belong to heavy pollution level, and total phosphorus only belongs to heavy pollution level in Xingyun Lake and Fuxian Lake. The results showed that the main sources of TP in Xingyun Lake are vigorous algae, rural non-point source pollution on both sides and the discharge of phosphorus chemical enterprises [21]. Similarly, the input rate of phosphorus in Fuxian Lake increased with the inhuman activity and algae proliferation [22].

(2) The pollution characteristics of heavy metals in lakes are basically consistent with the assessment of potential ecological risk characteristics. The pollution level of heavy metals in surface sediments is medium and below. The pollution elements are mainly Cu, Cd and Hg. The evaluation
results showed that Cd and Hg are the main contributing factors to the combined potential ecological risk of heavy metals, which are also obvious in other lakes and reservoirs in most cities of China[23][24].

(3) TN pollution has a strong correlation with lake recharge coefficient, population density and water depth. Heavy metal pollution mainly comes from the discharge of industrial and agricultural wastewater and the loss of elements in the soil of the basin. The sediments in lakes are formed by sediment, clay, organic matter and mineral mixtures which are deposited at the bottom of the water body through long-term physical, chemical and biological processes. This paper only gives the present situation of sediment pollution in different lakes and the phenomenal study of the relationship between pollution characteristics and related factors. In order to explore the pollution characteristics and influencing factors of surface sediment pollutants in deep lakes, it is necessary to carry out a deeper study on the mechanisms of different sources of external pollution, the conversion mechanism between "source" and "sink", the hydrologic and hydrodynamic characteristics of lakes, and the complicated sedimentary processes.

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