Spatial heterogeneity of water quality in a small watershed of an ionic rare earth mining area

Yonglin Chen\textsuperscript{a,b}, Yuxin Su\textsuperscript{a,b,*}, Haitao Li\textsuperscript{a,b}, Linxiu Cheng\textsuperscript{a,b}, Linfeng Guo\textsuperscript{a,b}, Leyao Zhang\textsuperscript{a} and Liying Ling\textsuperscript{a,b}

\textsuperscript{a}School of Geography and Environmental Engineering, Gannan Normal University, Ganzhou, Jiangxi 341000, China
\textsuperscript{b}Jiangxi Provincial Key Laboratory of Low-Carbon Solid Waste Recycling, School of Geography and Environmental Engineering, Gannan Normal University, Ganzhou 341000, China

\textsuperscript{*}Corresponding author. E-mail: tonystark_426@163.com

ABSTRACT

The tailwater of ion-type rare earth mines in southern Jiangxi has caused serious water pollution problems in small watersheds. In this study, seven physical and chemical indicators, namely, pH, TOC, dissolved oxygen, ammonia nitrogen, nitrate-nitrogen, salinity and redox potential were selected and spatial interpolation, principal component analysis, and geographic detector methods, were used to quantitatively analyze and evaluate the spatial heterogeneity of water quality in the small watersheds in this region. Tailwater pollution in the whole basin of the study area is serious. The spatial difference is manifested as east tributary > mainstream and reservoir area > southern tributary. Source pollution is the smallest, and water quality pollution is mainly manifested by excessive ammonia nitrogen, salinity, and TOC. The spatial differences in the physical and chemical properties of water bodies are significant. The distribution of ammonia nitrogen content is consistent with the spatial distribution of soil and water pollution, while nitrate-nitrogen is the opposite. Other indicators also show a certain spatial regularity, and the spatial regularity of dissolved oxygen content is not obvious. Water pollution in mining areas is mainly due to a large amount of ammonia nitrogen ions remaining in the mountains. As a result, the southern tributary ecological pool has an obvious purification effect on water quality. Salinity is extremely affected by ammonia nitrogen and TOC, oxidation-reduction potential is affected by pH and TOC, and TOC is influenced by ammonia nitrogen and pH. Salinity, ammonia nitrogen, and TOC are the potential risk factors of major pollution. The changes in the physical and chemical properties of the pollution index are not independent of each other. From the perspective of macro and micro, the comprehensive water pollution assessment system is adopted to provide a new idea for the prevention and control of rare earth industry tail water pollution, and further make exploratory efforts for the study of industrial wastewater pollution.

Key words: evaluation, Longnan Zudong, rare earth mining area, small watershed, spatial heterogeneity, water quality

HIGHLIGHTS

- Redox potential were selected and spatial interpolation, principal component analysis, and geographic detector methods.
- Tailwater pollution in the whole basin of the study area is serious, and the spatial difference is manifested as east tributary > mainstream and reservoir area > southern tributary.
1. INTRODUCTION

At present, in areas rich in mineral resources, mining has brought about a series of environmental problems such as deterioration of water quality, soil erosion, and soil pollution (Qiu et al. 2014), which also pose threats to human health (Fu et al. 2013). At the same time, industrial wastewater is rich in metal resources, which can be recycled as salt/mineral, so it has a high recycling value (Panagopoulos 2021a, 2021b). Water is an important resource for human existence and ecological environment. Environmental pollution in mines has received increasing attention, and scholars have conducted in-depth analyses of the social and environmental impacts of mining and processing (Saleem 2014). Because polluted industrial wastewater cannot be directly used for drinking water and industrial applications, the effective treatment of industrial salt water pollution is a great challenge facing the world. The zero liquid discharge (ZLD) desalination systems can be effective in the treatment and valorization of desalination brine (Panagopoulos 2021a, 2021b). An industrial symbiosis demonstration can be achieved using ZLD systems in which by-products of one industrial activity are turned into raw resources for another industrial activity (Panagopoulos 2022). These studies have made great contributions to solving global water pressure.

Rare earth is a very important national strategic resource for China. (So-called strategic resources means that the country does not need to import for future invasions or new wars. Instead, the country uses its usual strategic reserves of resources for war use. Examples of such resources are oil, natural gas, coal, steel, non-ferrous metals, rare earths, precious metals, and rare metals. However, the most important is oil, natural gas, and other energy sources.) The Gannan region in Jiangxi Province in China is rich in rare earth resources, and its ionic medium and heavy rare earths account for 80% of the country’s supply. It is known as the ‘kingdom of rare earth.’ The mining of rare earth in southern Jiangxi began in the 1970s and roughly experienced three processes: pool leaching, heap leaching, and in-situ leaching (Cheng & Che 2010). In-situ leaching is currently widely used due to its high leaching rate, low operating cost, and relatively less environmental damage (Zheng et al. 2020a, 2020b) in comparison with the other processes. The basic method is to dig a liquid hole in the longitudinal...
direction of the mountain and inject ammonium sulfate and other ammonium salt leaching agent from the liquid injection hole (Zhao et al. 2020). The leaching agent interacts with the rare earth elements in the ore body through ion exchange so that the rare earth elements enter the leaching mother liquor. The mother liquor is collected through the liquid collection system, and rare earths are uniformly extracted from the mother liquor (Xiao et al. 2015). A large amount of leaching solution infiltrates into the soil of the mining area, causing serious pollution of the surrounding water and soil by nitrogen compounds (Liu et al. 2015). Including pH reduction (Liu et al. 2014), rare-earth and heavy metals ions in the soil, river water, sediments, and farm soil (Liu et al. 2018; Liu et al. 2019a, 2019b) seriously exceed the standard, and the water quality of the basin was seriously affected.

In recent years, many scholars have conducted in-depth research on the spatial distribution of water pollution in the rare earth mining area in southern Jiangxi, and they have achieved fruitful results. Existing research shows that from the perspective of the horizontal spatial distribution along the watershed, the ammonia nitrogen content in the water flowing through the rare earth tailings area presents an obvious spatial gradient distribution with the increase of distance (Shi et al. 2020). The contents of ammonia nitrogen, nitrate nitrogen, and nitrite nitrogen tend to be consistent along the distribution and are negatively correlated with pH. The content of heavy metals in the mainstream is generally higher than that in the branch (Xu et al. 2020). The heavy metals Zn, Mn, As, Cd, and Pb may have certain homology. The content of ammonia nitrogen is closely related to the distribution of the heavy metals in the water (Liu et al. 2019a, 2019b). The content of Cd and Pb in the farmland soil along the river downstream of the mine in the basin exceeds the background value (Zhang et al. 2020). The rare earth elements are also distributed in bands as a whole (Ma 2018). The content of residual ammonium nitrogen and nitrate-nitrogen at the foot of the mountain is higher than those of the mountaintop and mountainside areas (Zheng et al. 2020a, 2020b). The residual heavy rare earth distribution in the mountain body decreases with the increase in depth (Zheng et al. 2020a, 2020b). Under different leaching water conditions, the content of ammonium nitrogen and total nitrogen in the surface rare earth soil decrease significantly, but the content in the deep soil was low and remained unchanged (Wang et al. 2014; Liu et al. 2015). The tailwater of rare earth mines also has a significant impact on the water quality of the Ganjiang River Basin. The Taojiang section has serious heavy metal pollution, which is related to the tungsten mines, rare earth mines, and aquaculture in the Tiaojiang River basin (Li et al. 2020). The existing research results suggest that the water quality of the rare earth mining area in southern Jiangxi is severely affected by mining. The content of ammonia nitrogen, heavy metals, and residual rare-earth ions all exceed the standard, and the spatial distribution also shows a certain regularity. Existing studies have analyzed the distribution regularity of horizontal and vertical space from the perspective of large-scale watersheds and explored the correlation between pollution indicators. Some studies have also analyzed the inducing factors, but they are insufficiently comprehensive. Analysis of the spatial differences in water quality in the basin on a small scale is rare, and the selection of water quality indicators is relatively simple. Many factors affect the water quality of a river basin at a large scale, especially in areas where human activities are more concentrated. The water quality of the river basin is closely related to the physical and chemical properties of the surrounding mountain soil, especially in rare earth mining areas. For these reasons, this study selects mines with relatively simple human activities (i.e., the only human activities are mining) as the research area. From the perspective of small watersheds, this study comprehensively considers the interrelationships of various physical and chemical indicators of water quality, systematically analyzes the spatial differences of water quality factors in the watershed and the reasons for their formation, and quantitatively evaluates the pollution levels in different areas. These processes can more accurately grasp the spatial distribution of water quality in the basin and the main components of water pollution can be found, thereby providing basic data and theoretical guidance for the follow-up prevention and control of rare earth mine tailwater pollution.

2. MATERIALS AND METHODS

2.1. Study area

This study selects the Zudong small watershed in Longnan County, Ganzhou City of China as the study area. The study area is located at the water end of Huangsha Village, approximately 10 km southeast of Longnan County (Figure 1), with an area of approximately 12.1 km². The original Zudong River flowed from west to east in the territory. In the 1970s, to mine rare earths, the local government dug out the river at the middle of the river (E114.85857°, N24.83195°), changing the direction of the original river. The direction of water flow west of the middle end was changed from west to east. The existing Zudong River is divided into two major tributaries, namely, south and east, which converge northward at the mid-end position.
and merge into the Gangbei Reservoir, forming a relatively closed small watershed. The average elevation of the study area is approximately 330 m. The terrain is high in the south and low in the north. It has a subtropical monsoon climate and is dominated by acid-red soil. The main vegetation types are mixed coniferous and broad-leaved forests with Masson pine and *Osmunda japonica* as the dominant species. No permanent residents are living in the study area, only a non-graded rural road can pass, and occasional vehicles travel in and out, and no other human activities occur. In the northern area of the Zudong River Basin, in-situ leaching technology was used to mine rare earth starting in 2000. The southwestern area has been mining rare earth since the 1990s, and some areas adopted mountain-moving pool leaching technology. Mining has caused mountain damage and serious soil erosion. In 2018, the local government completely stopped mining rare earth, and soil erosion was stopped and vegetation in the area was restored. The southern tributary adopted ecological pond restoration engineering measures to control the tailwater of the mining area.

### 2.2. Sample collection and pretreatment

Water quality samples were collected in the four regions of the Zudong River Basin, namely, the east tributary, the west tributary, the mainstream, and the reservoir area, on April 23–24, 2021, which was the wet period of the study area. A sample point was selected approximately every 500 m along the river using GPS to record its geographic location. Photos were taken to record the surrounding environmental characteristics of each sample point to determine the current water environment in the area. The locations of the sample points are shown in Figure 1.

The samples were taken from the surface water (0–20 cm) in the middle of the river to avoid mixing with floating substances. All the samples (2 L each) were stored in polyethylene bottles and transported back to the laboratory in a refrigerator and immediately placed in a 4 °C freezer.

### 2.3. Sample detection methods

The collected water sample was suction filtered with a filter membrane with a pore size of 0.45 μm to remove visible impurities and plankton in the water. Then, the obtained filtrate was put into a clean and dry polyethylene sample bottle to be stored for testing. Indicators such as pH, DO, ORP, and salinity are important reference standards for water quality
evaluation. The content can be used to quickly judge the water quality. It can be measured on-site with a YSI portable water quality analyzer (Professional Plus, USA). The contents of ammonia nitrogen and nitrate-nitrogen in the water sample were determined by a flow analyzer (AA3, SEAL Analytical, Tianjin Zhongtong Technology Development Co., Ltd). The total organic carbon (TOC) content was measured by a Jena TOC analyzer (multi N/C 2100, Germany). The chemicals used in the experiment were all high-grade pure, and ultrapure water was used in the analysis. The correlation coefficients of the standard curves are all up to 99.9%. All data were obtained through at least three experiments.

2.4. Data analysis and processing

2.4.1. Data visualization and spatial interpolation

The three-tone remote sensing image (with a resolution of 2 m) is used as the base map of the map. The spatial position of each sample point on the map is determined by the latitude and longitude position of each sample point, and the main physical and chemical properties measured by the sample are marked out on the map by the hierarchical display method. The grading method adopts the natural breakpoint method, which is divided into four levels, presented with symbols of different colors and sizes. Then, kriging interpolation is used to obtain the spatial distribution map according to the concentration values of the physical and chemical properties of the water quality sample points.

2.4.2. Principal component and correlation analysis

The KMO test and Bartlett spherical test were conducted for pH value, dissolved oxygen, ammonia nitrogen, TOC, nitrate-nitrogen, salinity, and redox potential of the samples using SPSS software. Principal component analysis was carried out for those with KMO > 0.5 and $P < 0.01$. The principal component factors were extracted according to the principle that the characteristic value was greater than 1. Bivariate correlation analysis was carried out on the nine physical and chemical properties using the Pearson correlation coefficient method.

2.4.3. Geodetector

Geodetector is a new statistical method proposed by Wang Jinfeng et al. to detect spatial differentiation and reveal the driving factors (Wang & Xu 2017). The method is widely used in natural sciences, social sciences, environmental sciences, and other fields. Geodetector can be used to explore the forces of influencing factors and the interaction between factors. Among them, the force of the influence factor is expressed by the value of $q$, which ranges from 0 to 1. The larger the value of $q$, the stronger the explanatory power of the factor on the dependent variable and vice versa. The interaction between factors reflects whether two different factors work together to increase or decrease the explanatory power of the dependent variable. Related literature (Wang & Xu 2017) provides the specific calculation formula.

3. RESULTS AND DISCUSSION

3.1. Spatial distribution law and cause of main water quality indicators

3.1.1. Ammonia and nitrate

The spatial distribution of ammonia nitrogen in the study area (Figure 2) mainly presents the following characteristics: (1) The ammonia nitrogen content in the whole basin exceeds the standard. According to the relevant regulations of the ‘Surface Water Environmental Quality Standards’ (GB3838-83) promulgated by the government in 2002, the target standard limit of Class V surface water is 2.0 mg/L and the average ammonia nitrogen content in the study area is 104.76 mg/L, which is over 50 times the limit. The minimum ammonia nitrogen content was 5.24 mg/L (sample point W20), and the maximum was 245.02 mg/L (sample point W12). (2) The ammonia nitrogen content presents the characteristics of east tributary > main stream and reservoir area > south tributary. The average value of nine sample points in the east tributary was 104.76 mg/L. The sample points W12 and W13 had the highest values in the whole basin, and algae and phytoplankton growth in the water body was considerable. The seven sample points of the southern tributary had relatively low ammonia nitrogen content with an average value of 15.66 mg/L. The eastern tributary was the major source of ammonia nitrogen in the mainstream and the reservoir area. The southern tributary shows a dilution effect on the concentration of ammonia nitrogen in the mainstream. (3) The ammonia nitrogen content at the source of the tributary was the lowest, and the content was high in the middle and lower reaches of the basin. The values of sample points W9, W19, and W20 were all below 10 mg/L. The ammonia content of the mainstream and reservoir area was relatively high with an average value of the seven sample points of 139.83 mg/L. These
results suggested that the self-purification capacity of the basin was limited, and the pollution pressure in the middle and lower reaches was increasing.

The key reason for the overall water quality of the entire river basin exceeding the standard of ammonia nitrogen was the large number of ammonium ions remaining in the mountains during the mining of rare earth tailings. For the southern tributary, after the mining area stopped mining, a series of tailwater treatment measures were adopted and a series of large-scale ecological purification ponds were built. The aquatic ecosystem in the ecological ponds has significantly improved, and the growth of emergent plants and phytoplankton has increased, resulting in the decrease of the ammonia nitrogen content. The east tributary has a large drainage area and a large amount of water, and it was mined for a long time. A huge amount of...
ammonia nitrogen ions in the tailings flowed into the water body. Effective tailwater treatment measures were not adopted, causing the ammonia nitrogen in the water body to seriously exceed the standard.

The spatial distribution of nitrate-nitrogen in the study area (Figure 2) mainly presents the following characteristics: (1) From the perspective of the area as a whole, the average value was 48.57 mg/L with the difference between the maximum value and the minimum value being only 29.4 mg/L, indicating that the overall difference in nitrate-nitrogen content was not remarkable. (2) From the perspective of regional differences, the nitrate-nitrogen content in the south tributary > mainstream and reservoir area > east tributary. Contrary to the spatial distribution of ammonia nitrogen content, the nitrate-nitrogen content in the southern tributary was higher than 55.08 mg/L. The nitrate-nitrogen content balance of the mainstream and reservoir area was between 40.33 and 55.07 mg/L, whereas the nitrate-nitrogen content of the east tributary was lower than 40.32 mg/L. (3) The maximum value appeared at the mid-end sample point W25 (value 60.87 mg/L) of the ecological pool, and the minimum value appeared at sample point W9 (value 31.47 mg/L) at the source point of the east tributary.

The southern branch has built an ecological pond with a broad water area, sufficient dissolved oxygen in the water, good growth of aquatic organisms, rapid conversion of NH₄⁺ into NO₃⁻ in the water, and a good purification effect of water quality. The low nitrate-nitrogen content of sample point W9 is due to the low impact of mining and the low ammonia nitrogen content in the water. Affected by the confluence of the east tributary and the south tributary, the nitrate-nitrogen content of the mainstream was somewhere in between. The TOC concentration in the mainstream is low, and the denitrification effect is not noteworthy. The ammonia nitrogen could not convert into nitrogen through denitrification, which causes the accumulation of nitrate-nitrogen in the water, resulting in a high concentration of nitrate-nitrogen.

### 3.1.2. pH and TOC

The spatial distribution characteristics of pH value (Figure 3) are as follows: (1) Except for some sample points outside the source, the pH value of the upstream is generally higher than the pH value of the downstream, and the downstream sample points W3, W4, W5, W6, W7, and the pH values of the source sample points W9, W20, W21, W22 are all lower than 6. (2) The sample points W10 and W11 have abnormal values, and the pH values are 10.5 and 8.1, respectively.

The surface water at the source of the river is mainly natural precipitation from the mines. A large amount of ammonium sulfate is used in the mining process, so the water quality is acidic. During the sampling process, a large amount of lime aqueous solution was artificially placed at the sample point W10 of the east tributary, causing abnormal pH values of W10 and W11. However, as the water continued to flow downstream, acidic wastewater continued to flow into it along the way. The pH value of the water body decreased, and the acidity was restored.

The spatial distribution characteristics of TOC content in the study area (Figure 3) are as follows: (1) From the perspective of regional differences, the TOC content shows the characteristics of east tributary > southern tributary > mainstream and reservoir area. The east tributary has characteristics of the source sample point W9. The TOC content in the region is higher than 6.86 mg/L, the TOC content in the south tributary is between 4.40 and 6.85 mg/L, and the TOC content in the mainstream and the reservoir area is lower than 4.39 mg/L. (2) The TOC content of sample points W12 and W13 is the largest at 17.5 and 18.15 mg/L, respectively. The minimum value appears at sample point W6 in the lake area with a value of 2.79 mg/L.

More bryophytes were observed in the east tributary, and more humus remains in the water, leading to an increase in TOC content in the water. By contrast, the concentration of nitrate in the south tributary is high, and the denitrification effect is remarkable, consuming TOC in the water, resulting in a low TOC concentration. The concentration of nitrate-nitrogen in the mainstream and the reservoir area further decreased. Such a decrease might be combined with denitrification to consume TOC in the water, resulting in the lowest TOC concentration.

### 3.1.3. Salinity and redox potential

The spatial distribution characteristics of salinity (Figure 4) are manifested as follows: (1) From the perspective of regional differences, the salinity distribution presents the characteristics of east tributary > reservoir area > mainstream > south tributary. The salinity of the east tributary and the reservoir area are both higher than 1.25 ppt/1000. The salinity of the mainstream is between 0.64 and 1.25 ppt/1000. The salinity of the southern tributary is lower than 0.64 ppt/1000. (2) The points with the highest salinity appear at the sample points W12 and W13 of the east tributary, with values of 2.2 and 2.14 ppt/1000, respectively.
An analysis of the cause of these results shows that the southern tributary ecological pond has a role in reducing salinity. Ammonium salt is converted into nitrogen through nitrification and denitrification, reducing the salt in the water, and the growth of aquatic plants needs to consume some nutrients. Therefore, the salinity is significantly lower but the flow velocity in the reservoir area slows down, the water area increases, and the water evaporates quickly, which is conducive to the accumulation of salt, so the salinity increases. However, the sample points W12 and W13 are artificially added with an aqueous lime solution, which caused an abnormal increase in the salt content in the water. With the supplement of surface water along the way, the salt content gradually decreased.

The spatial distribution characteristics of the oxidation-reduction potential (Figure 4) are displayed as several factors. The oxidation-reduction potentials are all positive, indicating no obvious anaerobic phenomenon in the water body, and the
sediments at all sampling points are in an aerobic state. From the perspective of regional differences, the redox potential of sample point W9 in the reservoir area and the source point of the east tributary is relatively high, exceeding 360.31 mv, and the redox potential of the middle end of the east tributary is relatively low, between 140.51 and 322.8 mv.

The reasons for this finding are that the water body in the small watershed has good fluidity and the river bed water level is low, so the dissolved oxygen in the water is high, resulting in a high oxidation-reduction potential. The sample point W9 has a low pollutant content, so the redox potential in the water body is high.

The dissolved oxygen content is generally high, exceeding 5 mg/L, and the water body is in a well-nourished state, but the spatial distribution characteristics are not significant, and the regularity is not conspicuous. The dissolved oxygen content

Figure 4 | Spatial distribution diagram of salinity and redox potential.
may be affected by the temperature, aquatic plants, and photosynthesis at the same time of sampling. The dissolved oxygen in the water body may change.

### 3.2. Correlation analysis of water quality physical and chemical indicators

A bivariate correlation analysis was carried out on seven physical and chemical indicators of water quality. The results showed the following: (1) With a *p*-value less than 0.05, salinity was positively correlated with ammonia nitrogen and TOC with correlation coefficients of 0.983 and 0.601, respectively. The oxidation-reduction potential was negatively correlated with pH and TOC, and the correlation coefficients were −0.786 and −0.563, respectively; (2) At the significance level of 0.01, TOC was positively correlated with ammonia nitrogen and pH, and the correlation coefficients were 0.514 and 0.442, respectively.

The results of correlation analysis suggest that the salinity in this area was mainly affected by ammonia nitrogen and TOC, the oxidation-reduction potential was significantly affected by pH and TOC, and the TOC was affected by ammonia nitrogen and pH. These results show that salinity mainly resulted from the ammonium salt and organic carbon in water may mainly come from humic acids, leading to a positive correlation between TOC and pH.

### 3.3. Principal component analysis of physical and chemical indexes of water quality

Principal component analysis of seven physical and chemical indicators (pH value, TOC, dissolved oxygen, ammonia nitrogen, nitrate-nitrogen, salinity, and redox potential) was conducted to extract two principal component factors. The cumulative variance contribution rate of these two principal component factors reached 67.608 (Table 1), and the load matrix of the two principal component factors was calculated (Table 2). As can be seen from Table 3 and Table 1, the nitrate nitrogen and oxidation-reduction potential in the main component F1 and the pH value in the main component F2 are negative, and the others are all positive. Nitrate nitrogen, oxidation-reduction potential, and pH value are therefore negatively correlated with other water pollution indicators and are not the main physical and chemical indicators that characterize the pollution of tailwater in rare earth mining areas. The ammonia nitrogen and salinity values in F1 and F2 and the TOC value in F1 are relatively high, both exceeding 0.2, indicating that ammonia nitrogen, salinity, and TOC are the main physical and chemical indicators for water pollution in this area.

After standard processing of each indicator, combined with the principal component factor score, the principal component comprehensive score of each sample point is calculated. The kriging method in ArcGIS software is applied to spatially interpolate the comprehensive scores of each point to obtain the spatial distribution map of water pollution in the basin (Figure 5). Figure 5 illustrates the following: (1) Regional differences were generally characterized by east tributary > main stream and reservoir area > south tributary. (2) The sample points W12 and W13 of the east tributary are the most polluted locations, and the sample points W9, W20, and W21 of the tributary source are the least polluted locations.

The east tributary basin has a long flow and a wide area, and no effective treatment measures are in place, and the pollution is serious. The ecological pond purification treatment technology of the southern tributary is effective and the pollution is relatively light. The mainstream and the reservoir area are affected by the confluence of the two tributaries, and the pollution degree is between these two areas. The amount of water at the source is small, and the accumulation of pollutants is small, so the pollution is the least.

### 3.4. Identification and analysis of potential risk factors of water pollution

To further explore the relationship between the comprehensive pollution index and the physical and chemical properties of water quality, the comprehensive score of the pollution index was taken as the dependent variable, and the physical and chemical indicators of water quality were taken as the independent variables to analyze the power of its potential risk factors.

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**Table 1 | Initial eigenvalues of each principal component**

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<th>Cumulative variance contribution rate %</th>
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<td>F2</td>
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Table 2 | Land matrix of principal components

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Table 3 | Correlation of physical and chemical indicators of water quality

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* and ** indicate significance *P < 0.05 and **P < 0.01.

Figure 5 | Spatial distribution map of the comprehensive score of pollution index.
and whether the two factors work together to increase or decrease the explanatory power of the influence on the concentration of pollutants.

Based on the analysis of potential risk factors affecting the concentration of ammonia nitrogen, the comprehensive q-value scores from high to low are salinity (0.81) > ammonia nitrogen (0.81) > TOC (0.79) > oxidation-reduction potential (0.54) > pH value (0.31) > nitrate-nitrogen (0.26) > dissolved oxygen (0.20). This result indicates that ammonia nitrogen and TOC are the main pollution potential risk factors, and their explanatory power is above 0.75. The analysis of the interaction of the two factors (Table 4) indicates that they all show bilinear enhancement (q(X1 ∩ X2) > Max(q(X1), q(X2))) or nonlinear enhancement (q(X1) ∩ X2) > q(X1) + q(X2)). No weakening effect and mutual independence were observed, indicating that the influence of various physical and chemical properties of water quality on the pollution index is not independent of each other. Any change in physical and chemical properties may affect other changes in physical and chemical properties, in turn affecting the change in pollution index.

4. CONCLUSION

Sampling and analysis of tailwater in the small watershed of the abandoned rare earth mining area in Longnan Zudong were conducted using ArcGIS software visualization and spatial interpolation methods, combined with SPSS software principal component analysis and geographic detector methods. The following conclusions are drawn. The whole basin of the study area has serious tailwater pollution, and its spatial differences are characterized by east tributary > main stream and reservoir area > south tributary. The least pollution is at the source, and the most serious pollution is at the sample points W12 and W13 of the east tributary. Water pollution is mainly manifested by excessive ammonia nitrogen, salinity, and TOC. According to the obtained spatial characteristics and main water pollutants, the main locations of rare earth mine tail water pollution can be clearly identified, and the corresponding pollution prevention measures can be taken in time. The spatial differences of the physical and chemical properties of water bodies are different. The distribution of ammonia nitrogen content is consistent with the spatial distribution of water pollution, which is expressed as east tributary > main stream and reservoir area > south tributary. The distribution of nitrate-nitrogen is the opposite, as south tributary > mainstream and reservoir area > east tributary. The TOC content is characterized by east tributary > southern tributary > mainstream and reservoir area. The pH value of the upstream is generally higher than the pH value of the downstream, and the pH value of the east tributary is obviously affected by human activity. Salinity presents the characteristics of east tributary > reservoir area > mainstream > southern tributary. The redox potential of sample point W9 at the source point of the reservoir area and east tributary is relatively high. The spatial regularity of dissolved oxygen content is not obvious. For the prevention and control of water pollution of rare earth mines, it is very important to present the water pollution status of the study area in all aspects through the spatial differences between specific physical and chemical properties of water bodies. Water pollution in the mining area is mainly caused by a large amount of ammonia nitrogen ions remaining in the mountains during the mining of rare earth tailings. The ecological pond in the south tributary has an obvious purification effect on water quality. The source water area is small, the accumulation of pollutants is small, and the pollution is lighter. An artificial lime solution is added. The neutralizing effect on the acidity of river water is limited. Artificial ecological restoration works have played a very effective role in the treatment of tailing water in rare earth mines. A large number of microorganisms cultured in a better ecological environment may be the reason for the alleviation of water pollution, and further relevant research is needed. Salinity, ammonia nitrogen, and TOC

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Two-factor interaction q value table</th>
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<tbody>
<tr>
<td></td>
<td>pH</td>
</tr>
<tr>
<td>pH</td>
<td>0.31</td>
</tr>
<tr>
<td>TOC</td>
<td>0.84</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
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</tr>
<tr>
<td>Ammonia</td>
<td>0.94</td>
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<tr>
<td>Nitrate</td>
<td>0.96</td>
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<tr>
<td>Salinity</td>
<td>0.96</td>
</tr>
<tr>
<td>Oxidation-reduction potential</td>
<td>0.82</td>
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</table>
are the potential risk factors of major pollution. The influences of various physical and chemical properties of water quality on the pollution index are not independent of each other. Any change in the physical and chemical properties may affect the changes in the pollution index. Therefore, the prevention and control of tail water pollution of rare earth mines cannot be carried out in a single way. Instead, the corresponding treatment scheme should be adopted based on the actual situation of the study area, or a variety of water pollution treatment methods should be combined to carry out all-round three-dimensional prevention and control measures. The results of this study are based on the detection and analysis of various physical and chemical properties indexes and pollution indexes of the water pollution in the rare earth mining area of Longnan County, and the comprehensive evaluation of the pollution situation in the study area, providing basic data and theoretical guidance for the treatment of tail water pollution in the rare earth mining area in the future. From the macro and micro perspectives, the research results can provide basic data support for the prevention and treatment of rare earth mine wastewater pollution, and provide methodological reference for future studies on the spatial and temporal distribution of small watershed wastewater.

Many factors affect water pollution in small watersheds in rare earth mining areas, and their mechanism of action is very complex. In particular, the main pollutants, namely, ammonia nitrogen and salinity, may also be affected by factors such as water temperature, flow rate, manual intervention, and seasonal changes. In future research, we should focus on the formation mechanism of water pollution in small watersheds in rare earth mining areas under the dual effects of the natural environment and human interference.

ACKNOWLEDGEMENTS
This research was supported by the science and technology project of Jiangxi provincial education department of China (Grant No. GJJ190761).

DECLARATION OF COMPETING INTEREST
The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT
Data cannot be made publicly available; readers should contact the corresponding author for details.

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First received 15 November 2021; accepted in revised form 28 March 2022. Available online 8 April 2022