ENVIRONMENTAL FORENSICS AND PRELIMINARY IMPACT ASSESSMENT OF WATER AND SOIL CONTAMINATION FROM RARE EARTH MINING IN MYANMAR

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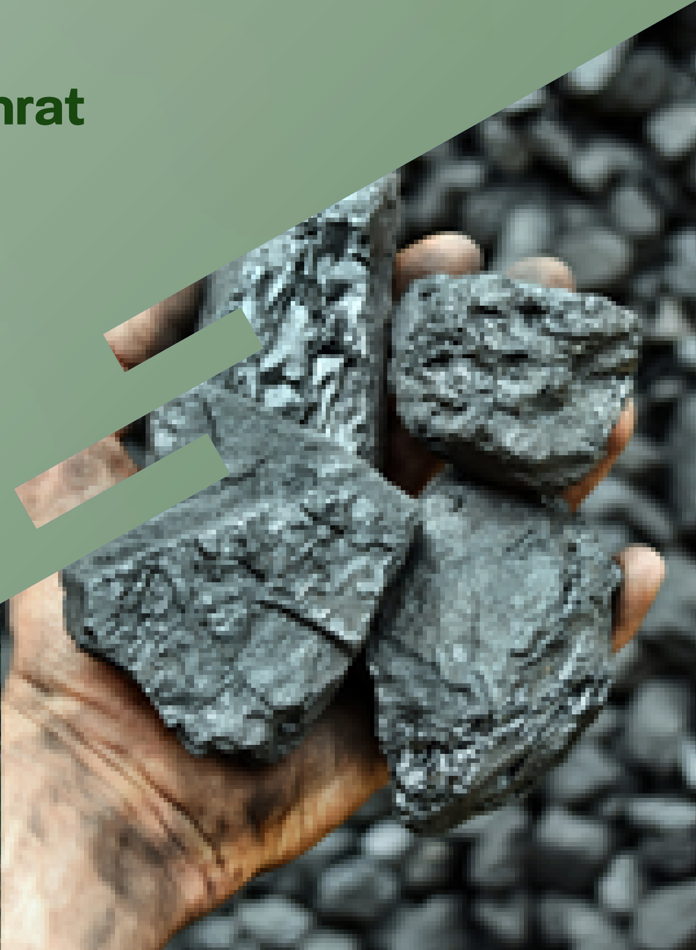

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Executive Summary

This report presents preliminary findings on environmental contamination resulting from rare earth mining in Kachin State, Myanmar, which has emerged as a significant global source of rare earth elements, particularly for export to China.

Analysis of surface water and topsoil samples from five sampling stations revealed severe contamination in water bodies associated with mining activities. Particularly at Station 2 (mine leachate) and Station 4 (direct mine discharge), extremely acidic pH levels (3.65 and 3.30 respectively) were detected along with alarmingly high concentrations of ionic species (ammonia, chloride), rare earth elements (dysprosium and terbium), radioactive elements (thorium and uranium), and toxic heavy metals.

The Water Quality Index (WQI) demonstrated that water from contaminated sites is entirely unsuitable for human consumption, irrigation, or fish culture without extensive treatment. Even at the furthest downstream sampling point (Station 5), water quality remains significantly degraded compared to the upstream reference site. The Potential Ecological Risk Index (PERI) further indicated that all studied metals and metalloids pose substantial risks to aquatic ecosystems.

Interestingly, topsoil samples showed minimal evidence of contamination, except for naturally occurring enrichment of thorium and uranium. This finding supports the hypothesis that contamination primarily occurs through subsurface migration, drainage from high-elevation mining sites, or direct discharge into streams, rather than surface runoff.

When compared to China's newly published national standards for water pollution control from in-situ leaching of ionic rare earth mines (April 2024), the severely contaminated water at Stations 2 and 4 far exceeds the established limits. Even Station 5, the furthest downstream point, shows contamination levels that would not meet these regulatory standards.

These findings underscore the urgent need for stringent management of leachate and direct discharge from rare earth mining operations, coupled with comprehensive monitoring of downstream water quality. Rigorous regulatory frameworks and comprehensive remediation approaches are necessary in areas affected by rare earth mining activities.

1. Introduction

Rare earth elements (REEs) have become increasingly vital components in a wide range of modern technologies, including electric vehicles, digital products, and renewable energy systems (Balaram, 2019). As the global demand for these critical materials continues to grow, the search for new sources of REEs has intensified. Historically, China has dominated the rare earth production market (Figure 1). However, in recent years, Myanmar has emerged as a significant exporter of rare earth elements to China, accounting for 38% of Chinese imports in 2023 (Reuters, 2023). From 2014 to 2021, the value of rare earth mined in Myanmar increased by an astonishing 520 times (Global Witness, 2022).

The Global Witness report (2022) reveals that the rapid expansion of the industry has been accompanied by human rights abuses, land grabs, and the displacement of local communities. The lack of transparency and accountability in the mining sector has further exacerbated these issues, highlighting the need for improved governance and regulation (Yan et al., 2013). Similar socio-economic challenges have been observed in other regions of the world where rare earth mining takes place, such as China (Packey and Kingsnorth, 2016), the United States (Standaert, 2019), and Australia (Ali, 2014). These issues underscore the importance of responsible mining practices and the need for a holistic approach that considers not only the economic benefits but also the social and environmental consequences of rare earth mining (Ali, 2014).

A part of the socio-economic analysis of rare earth mining in Myanmar involves appropriate environmental and human impacts assessment. According to a report by Global Witness (2022), the mining of dysprosium (Dy) and terbium (Tb), two essential REEs, has led to widespread environmental contamination and posed significant risks to the health and well-being of local communities in Kachin State, Myanmar.

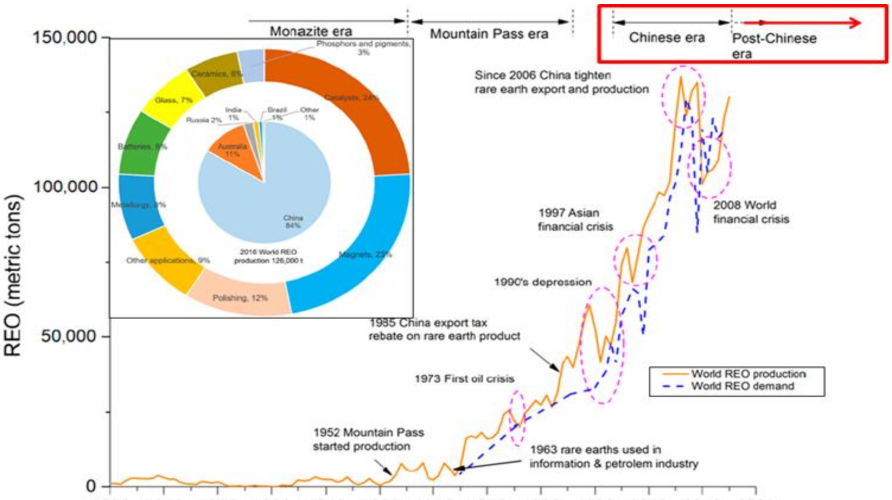


Figure 1 Historical global rare earth production and demand (1900-2020) and the distribution of global rare earth production and consumption in 2015 (Zhou et al., 2017)

This is because the process of mining Dy and Tb involves several stages, including exploration, extraction, beneficiation, and refining, all of which cause environmental disturbance and waste generation (ELAW, 2023). In Myanmar, the most common methods for extracting these elements are open-pit mining, underground mining, and in-situ leaching. Open-pit mining involves the removal of topsoil and the transportation of ore to leaching ponds, where acids and chemicals are used to separate the rare earth elements from the clay, soil, and rock. On the other hand, in-situ leaching, involves the injection of chemicals such as ammonium sulphate ($(NH_4)_2SO_4$), ammonium chloride (NH_4Cl), or other leachants into wells perpendicular to the mines. The pregnant solution containing the rare earth ions as well as other toxic elements then flows out through drains into ponds for further extraction (ELAW, 2023; Vahidi et al., 2016). As illustrated in Figure 2 and 3, in-situ leaching can lead to soil acidification, ammonia contamination, and the leaching of metals and rare earth elements into groundwater and surface water (Liu et al., 2022; Zhang et al., 2020). On the other hand, mine tailing and mine waste from open-pit mining can cause contaminated run-off during rainy season. Moreover, direct discharge of mine water from open-pit mining can directly cause surface water contamination.

Next to the extraction step, as shown in Figure 2, the mineral processing and mine tailing management also generate a significant amount of toxic waste, including radioactive materials, heavy metals, and other pollutants (ELAW, 2023; Rim et al., 2013). The release of these contaminants into the environment can result in the contamination of soil, water, and air, posing significant threats to human health and aquatic ecosystems (Gwenzi et al., 2018). These environmental consequences can have long-lasting effects on the local ecosystem and the health of nearby communities. The contamination of water resources is especially alarming, as it can compromise not only the availability of safe drinking water but also pose risks to aquatic life (Liang et al., 2014). Human exposure to these contaminants can also occur through inhalation of dust and particulate matter, direct chemical exposure in addition to the consumption of contaminated water or food (Gwenzi et al., 2018; ELAW, 2023). The health effects associated with exposure to Dy and Tb can be severe. Prolonged exposure to high levels of these elements can cause lung obstruction, cancer, and other respiratory issues in mine workers and local communities (Shirazi et al., 2022). Moreover, not only the exposure to REEs, the release and uptake of unwanted by-products such as radioactive elements such as thorium and uranium and toxic metals and metalloids are known to increase the risk of various health problems, both cancer and non-cancer (ELAW, 2023; Ragheb, 2020; Yin, et al.,2021).

In light of these concerns, this study aims to preliminarily assess the potential water and soil contamination caused by rare earth mines in Kachin, Myanmar, using geochemically environmental forensics. The primary objectives of this project are:

- To assess potential water and soil contamination caused by rare earth mines in Kachin, Myanmar via geochemically environmental forensics
- To preliminarily assess environmental impacts associated with water and soil contamination caused by rare earth mines in Kachin, Myanmar

By conducting a screening investigation of the environmental contamination resulting from rare earth mining in Myanmar, this study seeks to provide crucial insights into the extent and severity of the problem. We hope that the findings of this research will urge responsible parties and government agencies to develop strategies for mitigating the environmental and health risks associated with rare earth mining and promote the adoption of more sustainable and responsible mining practices in the region. Furthermore, the results of this study can inform policy decisions and support the development of stronger regulations to protect the environment and the rights of local communities affected by rare earth mining activities. As China recently published its first national Water Pollution Control Standard for In-situ Leaching of Ionic Rare Earth Mines (April 2024), this study also provides an opportunity to evaluate Myanmar's rare earth mining practices against emerging international standards, particularly those of China, which is the primary destination for Myanmar's rare earth exports.

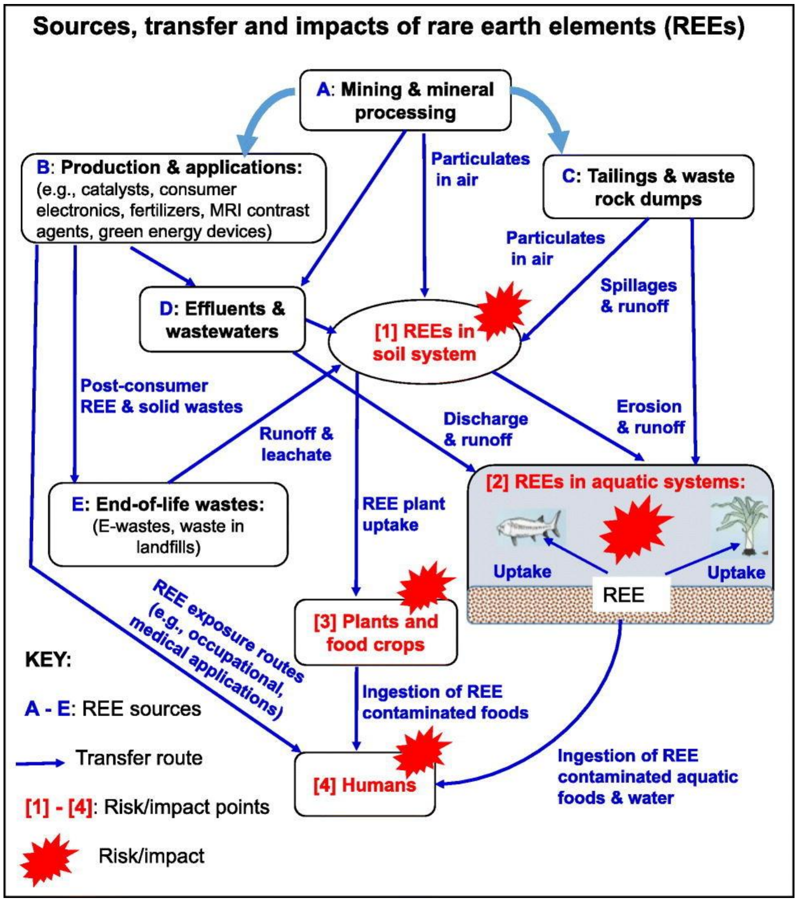


Figure 2 Source, transfer, and impact of REE mining (Gwenzi et al.,2018)

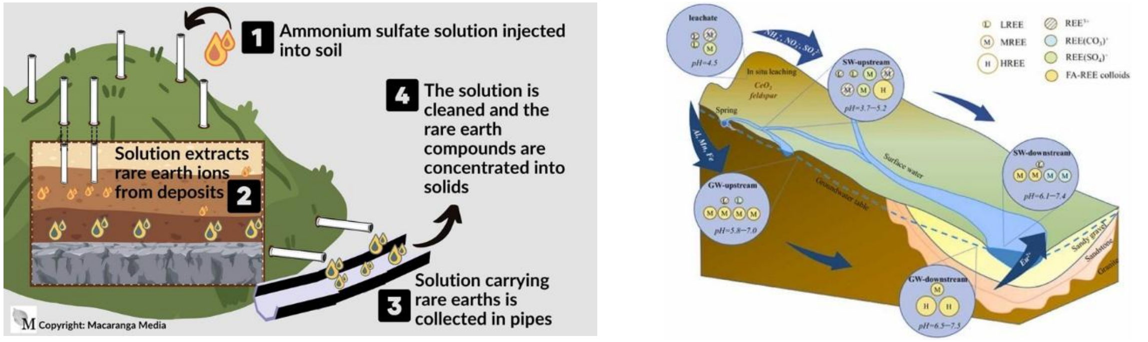


Figure 3 (a) In situ leaching for REE mining and (b) soil, groundwater, and surface contamination by REE mining either by in situ leaching or by contaminated run-off (Liu et al.,2022)

2. Conceptual Model, Approach, and Chemical Analysis

2.1 Conceptual Model

The surface water contamination caused by rare earth mining in Myanmar may occur through four possible pathways (Liang et al., 2016; Hou et al., 2017):

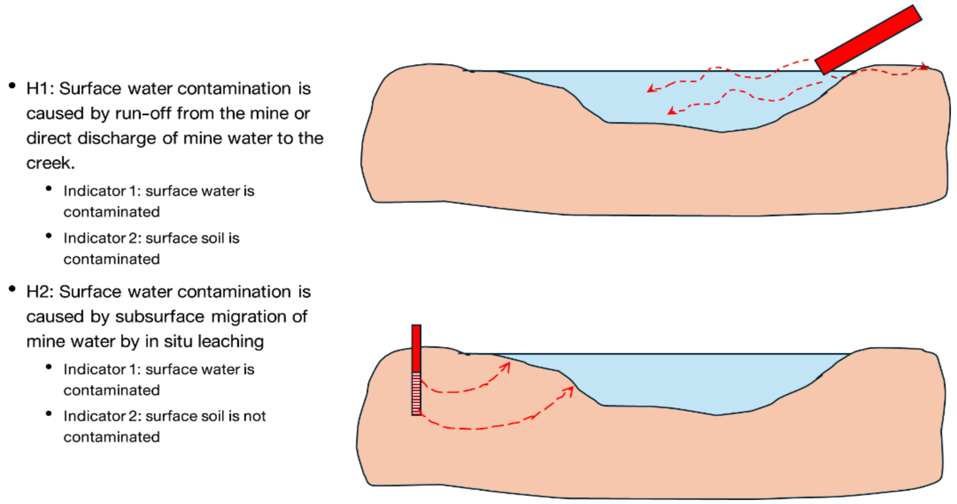
1. Subsurface migration of contaminated mine water from in-situ leaching to nearby creeks
2. Drainage from high-elevation in-situ leaching sites to surface water
3. Runoff of contaminated water from open-pit mining areas to nearby creeks
4. Direct discharge of mine water from sedimentation ponds into nearby creeks or water bodies

The conceptual model for this study considers these four pathways in two possible hypotheses, H1 and H2, as illustrated in Figure 4. The main difference between these hypotheses is the extent of surface soil contamination.

Hypothesis 1 (H1) suggests that surface water contamination is caused by runoff from the mine. If this hypothesis is true, we would detect contamination in both surface water and surface soil because contaminated runoff and drainage would leave evidence of surface soil contamination along the migration path.

Hypothesis 2 (H2) proposes that surface water contamination is caused either by subsurface migration of mine water through in-situ leaching, by drainage from high-elevation in-situ leaching sites to surface water, or by direct discharge of mine water from the sedimentation pond to the creek. If this hypothesis is correct, surface water contamination will be detected, but surface soil contamination will not be observed because subsurface leaching or direct mine water discharge to the creek does not directly affect the surface soil.

To preliminarily test these hypotheses, we will collect and analyze samples of surface water and surface soil from the affected area. The results will provide screening evidence to support either H1 or H2, helping to identify the primary pathway of surface water contamination caused by rare earth mining in Myanmar.



- H1: Surface water contamination is caused by run-off from the mine or direct discharge of mine water to the creek.
  - Indicator 1: surface water is contaminated
  - Indicator 2: surface soil is contaminated
- H2: Surface water contamination is caused by subsurface migration of mine water by in situ leaching
  - Indicator 1: surface water is contaminated
  - Indicator 2: surface soil is not contaminated

Figure 4 Two possible hypothesis explaining surface water contamination as well as their indicators

2.2 Approach

For this purpose, a comprehensive set of geochemical parameters in soil and surface water have been selected, as shown in the Table 1. These parameters are chosen based on their relevance to the environmental impacts associated with in-situ leaching and contaminated mine water from open-pit mining as also shown in Table 1 (Moldoveanu & Papangelakis, 2012).

Table 1 Relevant geochemical parameters for environmental forensics in this project together with their rationales

Geochemical Parameter	Environmental Media	Rational	Reference
pH	Water and Soil (pore water)	In situ leaching makes soil and water acidic	Zhang et al., 2020
Ammonia, Nitrite, Sulfate,		Leaching solution	
Ionic species: Cl, F, Alkalinity, Total dissolved solid		Leached by in situ leaching	Zheng et al., 2023
Metals and metalloids (toxic): As, Cd, Cr, Co, Cu, Fe, Pb, Mn, Ni, Se, Sr, V, Zn		Leached by in situ leaching and hazardous to health and environment	Liu et al, 2022
Rare earth: Dysprosium, Terbium		main rare earth elements in Myanmar	Global Witness, 2022
Radioactive: Thorium, Uranium		Typically contaminated by rare earth mining	Patel et al., 2023

Briefly, rare earth elements, specifically Dy and Tb, in soil and surface water are the primary targets in this study and thus are the main indicators of contamination from REE mining in this study (Global Witness, 2022). The pH of water and soil (pore water) is a crucial indicator of the acidification caused by in-situ leaching, as the process can significantly lower the pH of the surrounding environment (Zhang et al., 2020; Liao et al., 2016). Ammonia, nitrite, sulfate, and other ionic species such as chloride, fluoride, alkalinity, and total dissolved solids are often present in the leaching solution and can be leached into the environment during the mining process (Galachieva et al., 2022; Thomas et al., 2022). These contaminants can have detrimental effects on water quality, soil health, and aquatic ecosystems (Liang et al., 2014).

Metals and metalloids, including arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, selenium, strontium, vanadium, and zinc, can be leached either in-situ leaching or ex situ leaching of open-pit mining. These elements pose significant hazards to human health and the environment (Liu et al., 2022). These elements can accumulate in the food chain, leading to potential health risks for humans and wildlife (Rim et al., 2013; Li et al., 2013). The environmental fate and toxicity of rare earth elements have been a growing concern in recent years (Pagano et al., 2015; Gwenzi et al., 2018). Additionally, radioactive elements such as thorium (Th) and uranium (U) are typically associated with rare earth mining and can contribute to environmental contamination (Patel et al., 2023; Ragheb, 2020).

Five sampling locations were chosen to represent mine discharges, surface water, and soil at different levels of contamination based on their proximity to the mining sites, as shown in Figure 5 and Table 2. The sampling stations are as follows:

- Station 1 serves as the upstream reference site, representing natural background conditions.
- Station 2 is the drainage from in-situ leaching at the mine, expected to exhibit high levels of contamination.
- Station 3 is situated in a heavily contaminated area, based on local knowledge and observations.
- Station 4 is the direct discharge of mine water from a sedimentation pond.
- Station 5 is located further downstream to assess the extent of contamination migration and attenuation.

The selection of sampling locations based on contamination levels and proximity to pollution sources is a common approach in environmental assessment studies (Giri & Singh, 2014; Varol & Şen, 2012). Furthermore, this study conducted spatial analyses to address the following key questions:

- Existence of Contamination: Are there indications of environmental contamination resulting from rare earth mining activities in Myanmar?
- Source of Contamination: Is the observed contamination directly attributed to mining activities, or is it primarily of natural origin with minimal mining-related contribution or acceleration?
- Potential contamination pathway: Could the contamination pathway be either from subsurface to surface water or from run-off to surface water?
- Extent of Concern: How concerning is the identified contamination in terms of its impact on ecosystems, human health, and environmental sustainability?

Furthermore, to supplement the spatial comparison of raw data, several indices were employed to interpret the results and address the four key questions, as outlined in Table 3.

Briefly, the Contamination Factor (CF) (Eq.1) and Modified Degree of Contamination (Eq.2) will be used to evaluate the degree of surface water contamination caused by individual elements and the overall contamination level, respectively, relative to the upstream background concentration (Hakanson, 1980; Abrahim & Parker, 2008). These indices have been widely used in environmental assessment studies to quantify the extent of contamination in various environmental media (Karbassi et al., 2008; Varol, 2011).

$$CF_i = \frac{C_i}{C_{Bi}} \quad (1)$$

Where C_i is concentration of contaminant i at the mining-impacted locations (Station 2, 3, and 4), and C_{Bi} is concentration of contaminant i at the natural background (Station 1). Both total and dissolved concentrations were used for C_i and C_{Bi} for calculation of the two versions of CF (total CF (CF_{Ti}) and dissolved CF (CF_{Di})). Table 4 summarizes the level of CF, their interpretation, and their color scheme.

$$mC_d = \frac{\sum_{i=1}^{n} CF_i}{n} \quad (2)$$

Where CF_i is Contamination factor (CF) of an element i at a particular station, and n is number of analyzed trace elements. Table 5 summarizes the level of mC_d, their interpretation, and their color scheme.

Figure 5 (a) Map of 5 different sampling stations from upstream (Station 1(b)), mine water (Stations 2 (b) and 4 (e)), and downstream (Stations 3 (d) and 5(f))

Table 2 Station 1 to 5 and their coordinates

Station No.	Sample Type	Date of Collection	Location	Remark
1	water	Feb 14, 2024	UTM 47R 438908 2833613	The stream flowing from Pang Wa mountain area. Watershed of Pang Wa area.
1	water	Feb 14 2024	UTM 47R 426356 2841112	Drinking water from mining sites.
1	soil	Feb 14, 2024	UTM 47R 438895 2833603	No mining impact area near community farm.
2	water	Feb 12, 2024	UTM 47R 434943 2838101	Old mining site (More than 10 years old).
2	soil	Feb 12, 2024	UTM 47R 430459 2845100	Old mining site.
3	water	Feb 12, 2024	UTM 47R 433287 2842774	Meet point area of two creeks. Sau Lang creek and Chiphwi creek, Contaminated By mining site, flowing to May Kha River.
3	soil	Feb 12, 2024	UTM 47R 433296 2842752	The bank of Chiphwi creek area.
4	water	Feb 14, 2024	UTM 47R 425940 2841368	Take water sample from new rare earth operation mining site.
4	soil	Feb 14, 2024	UTM 47R 426340 2841115	Near new operation mining site.
5	water	Feb 15, 2024	UTM 47R 416377 2861253	Dashi creek near Yit Kyaw village flowing to Chiphwi creek.
5	soil	Feb 15, 2024	UTM 47R 416375 2861249	Village.

Table 3 Important indices and their meanings

Question Answered	Index	Meaning	Reference
Is there any contamination in surface water?	Contamination Factor (CF)	The degree of surface water contamination in mining areas by each relevant element, relative to the upstream background concentration	Hakanson, L.(1980). An ecological risk index for aquatic pollution control.a sedimentological approach, Water Research,14 (8), 975-1001, https://doi.org/10.1016/0043-1354(80)90143-8.
	Modified Degree of Contamination (mCd)	The degree of surface water contamination in mining areas by all relevant elements, relative to the upstream background concentration.	Abrahim GMS, Parker RJ (2008) Assessment of heavy metal enrichment factors and the degree of contamination in marine sediments from Tamaki Estuary, Auckland New Zealand. Environ Monit Assess 136(1–3):227–238
Does surface water contamination compromise its quality for human use?	Water Quality Index (WQI)	The degree of surface water quality impact by mining activity	Tiwari, T.N., Mishra, M., 1985. A preliminary assignment of water quality index of major Indian rivers. Indian J. Environ. Prot. 5 (4), 276–279.
Is the aquatic ecology at risk?	Potential Ecological Risk Index (PERI)	The degree of potential aquatic ecological impact by mining activity	Cui, L., Wang, X., Li, J., Gao, X., Zhang, J., Liu, Z., 2021. Ecological and health risk assessments and water quality criteria of heavy metals in the Haihe river. Environ. Pollut. 290, 117971.

Table 4 Interpretation of CF and its color scheme

CF	Level of Contamination	Color Scale
<1	Low	🟩
1-3	Moderate	🟨
3-6	considerable contamination	🟧
>6	very high contamination	🟥

Table 5 Interpretation of mC_d and its color scheme

mC_d	Contamination status	Color Scale
< 1.5	Nil to a very low degree of contamination	🟩
1.5-2	Low degree of contamination	🟧
2-4	A moderate degree of contamination	🟧
4-8	A high degree of contamination	🟨
8-16	A very high degree of contamination	🟧
16-32	An extremely high degree of contamination	🟥
>32	Ultrahigh degree of contamination	🟥

On the other hand, the Water Quality Index (WQI) (Eq.3) will be calculated to determine the extent to which surface water contamination compromises its quality for human use, such as drinking, irrigation, and industrial purposes (Tiwari & Mishra, 1985). The WQI integrates multiple water quality parameters into a single value, providing a comprehensive assessment of water quality (Tyagi et al., 2013). The Potential Ecological Risk Index (PERI) (Eq.4) will be employed to assess the potential risk posed by the contamination to aquatic ecology (Cui et al., 2021). The PERI considers the toxicity and environmental behavior of individual contaminants to estimate the potential ecological risk (Wang et al., 2018; Yi et al., 2011).

$$WQI = \sum_{i=1}^{n} \left[W_i \times \frac{C_i}{S_i} \right] \times 100 \qquad (3)$$

Where C_i is actual concentration of parameter i at the sampling locations, and S_i is drinking water standard of parameter i. Table 6 summarizes the level of WQI, their interpretation, and their color scheme.

Table 6 Interpretation of WQI and its color scheme

WQI	Water quality status (WQS)	Intended Usage			Color Scale
		Drinking	Irrigation	Industrial	
0-25	Great	Suitable	Suitable	Suitable	🟩
25-50	Good	Suitable	Suitable	Suitable	🟨
50-75	Poor	Not suitable	Suitable	Suitable	🟧
75-100	Very Poor	Not suitable	Suitable	Not suitable	🟥
Above 100	Not suitable for drinking or fish culture	Proper treatment is required			🟥

$$PERI = \frac{C_i}{ACL_i} \tag{4}$$

Where C_i is actual concentration of i in surface water, and ACL_i is aquatic life criterion values of 8 trace elements by Cui et al. (2021). Table 7 summarizes the level of PERI, their interpretation, and their color scheme.

To further investigate the source and nature of contamination, sequential extraction of soil samples were performed, as outlined in Table 8. This process helps differentiate between the mobile, potentially bioavailable fractions (F1 and F2) and the more stable, residual fractions (F3, F4, and F5) of metals, metalloids, and rare earth elements in the soil (Liang et al., 2014; Tessier et al., 1979). The sequential extraction procedure provides valuable information on the potential mobility, bioavailability, and environmental risk associated with the contaminants (Filgueiras et al., 2002; Okoro et al., 2012).

Table 7 Interpretation of PERI and its color scheme

PERI	Level of Contamination	Color Scale
<0.1	Low	🟩
0.1-1	Moderate	🟨
1-10	considerable contamination	🟧
>10	very high contamination	🟥

Table 8 Procedure for sequential extraction

Fraction No.	Fractions	Procedure
F1	Exchangeable fraction	0.5 g soil + 8 mL of 1 mol L-1 MgCl2 (pH = 7), shaking time: 1 h, room temperature
F2	Carbonate fraction	Residue + 8 mL of 1 mol L^{-1} CH3 COONa (pH=5.0 with CH$_3$COOH), shaking time : 16 h, room temperature
F3	Fe-Mn oxides	Residue + 20 mL of 0.04 mol L-1 NH$_2$OH•HCl in 25% CH$_3$COOH (pH = 2), shaking time: 6 h, 96°C
F4	Organic fraction	Residue + 3 mL of 8.8 mol L^{-1} H$_2$O$_2$ + 5 mL 0.02 mol L^{-1} HNO$_3$ (pH=2.0), 85°C, 3h; + 3 mL of 8.8 mol L^{-1} H$_2$O$_2$, 85°C 3h; + 5 mL 3.2 mol L^{-1} of CH$_3$COONH$_4$, shaking time: 16 h, room temperature
F5	Residual fraction	digested with 10 mL of 65% nitric acid

2.3 Chemical Analysis

A total of 150 analytical results were obtained from the study. For each of the five sampling locations, water and soil samples were collected in duplicate. Water and soil samples were collected and analyzed for pH, ORP, EC, and TDS using standard methods such as EPA Method 150.1 for pH (US EPA, 1983), EPA Method 120.1 for EC (US EPA, 1982), and EPA Method 160.1 for TDS (US EPA, 1971). TSS was determined using EPA Method 160.2 (US EPA, 1971). Ammonia and nitrite concentrations were measured using EPA Method 350.1 (US EPA, 1983) and EPA Method 354.1 (US EPA, 1971), respectively. Fluoride levels were assessed using EPA Method 340.2 (US EPA, 1974). Metals, metalloids, rare earth elements, and radioactive elements were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) following EPA Method 200.8 (US EPA, 1994). These standard methods ensure the reliability and comparability of the analytical results (Clesceri et al., 1998; APHA, 2017).

Sequential extraction of soil samples was performed to determine the distribution of metals, metalloids, and rare earth elements among different geochemical fractions, as described earlier. The five-step sequential extraction procedure, adapted from Tessier et al. (1979), included the following fractions: exchangeable (F1), carbonate-bound (F2), Fe-Mn oxide-bound (F3), organic-bound (F4), and residual (F5). Each fraction was extracted using specific reagents and conditions, and the extracts were analyzed for the target elements using ICP-MS. Quality assurance and quality control (QA/QC) measures were implemented throughout the sampling and analytical processes to ensure the accuracy and precision of the results. Laboratory quality control samples, including method blanks, laboratory control samples, matrix spikes, and duplicates, were analyzed to evaluate the performance of the analytical methods (US EPA, 2001). Certified reference materials were used to validate the accuracy of the ICP-MS analyses (Linsinger et al., 2001).

The use of multiple sample replicates and a wide range of analytical parameters ensures the reliability and representativeness of the data (Thompson, 2012). The data obtained from the geochemical analyses and sequential extraction were used to calculate the environmental indices elaborated earlier. These indices provide a comprehensive assessment of the contamination levels, water quality, and potential ecological risks associated with rare earth mining in the study area. The use of multiple indices allows for a more robust evaluation of the environmental impacts (Audry et al., 2004; Yi et al., 2011).

3. Results and Discussion

3.1 Surface water contamination

3.1.1 pH and Ionic Species

The results of the geochemical analysis reveal clear signs of contamination caused by rare earth mining activities, with varying degrees of impact across the sampling locations (see Figure 6) .

Leachate and Direct Discharge (Stations 2 and 4):

The leachate from rare earth mining (Station 2) and the direct discharge from the mine to the sedimentation pond (Station 4) showed extremely acidic pH levels of 3.65 and 3.30, respectively. This severe acidification is a direct consequence of the in-situ leaching process, which introduces highly acidic solutions into the environment (Zhang et al., 2020; Liao et al., 2016). The concentrations of ionic species associated with the rare earth mining leaching solution, such as ammonia (NH_3) and chloride (Cl^-) (Figure 6), were alarmingly elevated at these stations. The contamination factor (CF) for NH_3 reached as high as 29.8 at Station 4, while the CF for Cl^- peaked at 238 at the same location. These exceptionally high CF values indicate severe contamination of the leachate and direct discharge by the mining process (Liang et al., 2014).

Upstream Reference (Station 1):

In contrast, the upstream reference site (Station 1) showed minimal signs of contamination, with a pH of 6.88, which is within the normal range for natural surface waters. This station served as a baseline, representing the natural background conditions of the area before the influence of mining activities.

Midstream and Downstream (Stations 3 and 5):

The midstream (Station 3) and downstream (Station 5) sampling points exhibited clear evidence of acid contamination, though to a lesser extent than the leachate and direct discharge. While Station 2 and 4 exhibited high concentrations of mining-related contaminants, Station 3 (midstream) sometimes showed equal or higher concentrations for certain parameters. This pattern suggests that Station 3 may be receiving additional contamination inputs beyond those measured at Station 2, potentially from multiple mining operations in the area or from sediment re-suspension of previously deposited contaminants. Station 5, further downstream, showed signs of partial recovery, with water quality parameters improving compared to Station 3, but still not returning to background levels.

The concentrations of ionic species (NH_3 and Cl^-) at Stations 3 and 5 (Figure 6) were elevated compared to the upstream reference, but lower than in the leachate and direct discharge. At Station 3, the CF for NH_3 was 5.36, and for Cl^- it was 20, indicating substantial contamination but at levels considerably lower than those observed in the leachate and direct discharge.

These findings are consistent with other studies on rare earth mining impacts. Similar acidification of surface water due to rare earth mining has been reported in southern China (Zhang et al., 2020) and Malaysia (Elias et al., 2019). The presence of elevated levels of ionic species in surface water near rare earth mining sites has been documented in previous studies, highlighting their potential as indicators of contamination (Liu et al., 2018; Liu et al., 2021; Moldovan et al., 2022).

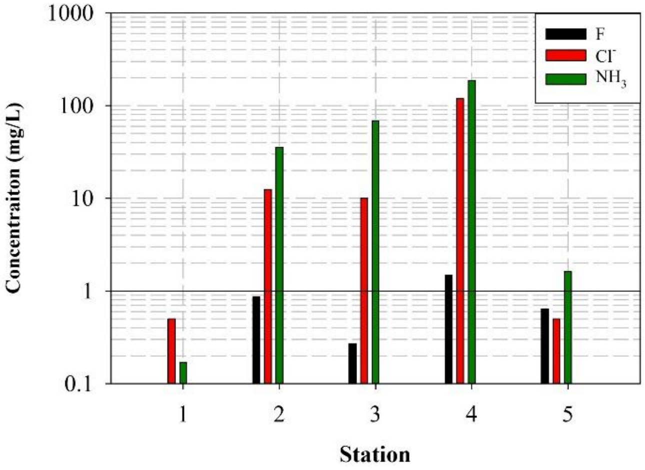


Figure 6 Total fluoride, chloride, and ammonia concentration in water from Station 1 to 5

3.1.2 REES, Radioactive Elements, Metals, and Metalloids

Similarly, the presence of rare earth elements (REEs), radioactive elements, and toxic metals and metalloids in the water samples provides strong evidence of contamination from rare earth mining activities, with varying degrees of impact across the sampling locations (Figure 7 to 9).

Leachate and Direct Discharge (Stations 2 and 4):

The leachate from rare earth mining (Station 2) and the direct discharge from the mine to the sedimentation pond (Station 4) showed extremely high concentrations of REEs, radioactive elements, and toxic metals. The contamination factors (CF) for dysprosium (Dy) and terbium (Tb) reached up to 6,468 and 13.1, respectively, while the CF values for thorium (Th) and uranium (U) were as high as 2,147 and 21,899, respectively. These exceptionally high CF values indicate severe contamination directly attributable to mining activities. Similarly, the concentrations of toxic metals and metalloids such as arsenic, cadmium, chromium, manganese, nickel, lead, and strontium were alarmingly elevated in these samples. The CF values for these elements were exceptionally high, far exceeding those observed at other sampling points. Notably, a significant portion of these elements was found in the dissolved phase (88% for U, 87% for Dy, and 81% for Tb, 58% for As, 80% for Cd, and 84% for Sr) (Figure 7), suggesting that their presence is primarily due to the mining processes rather than natural sources or weathering (Liang et al., 2016; Liu et al., 2022).

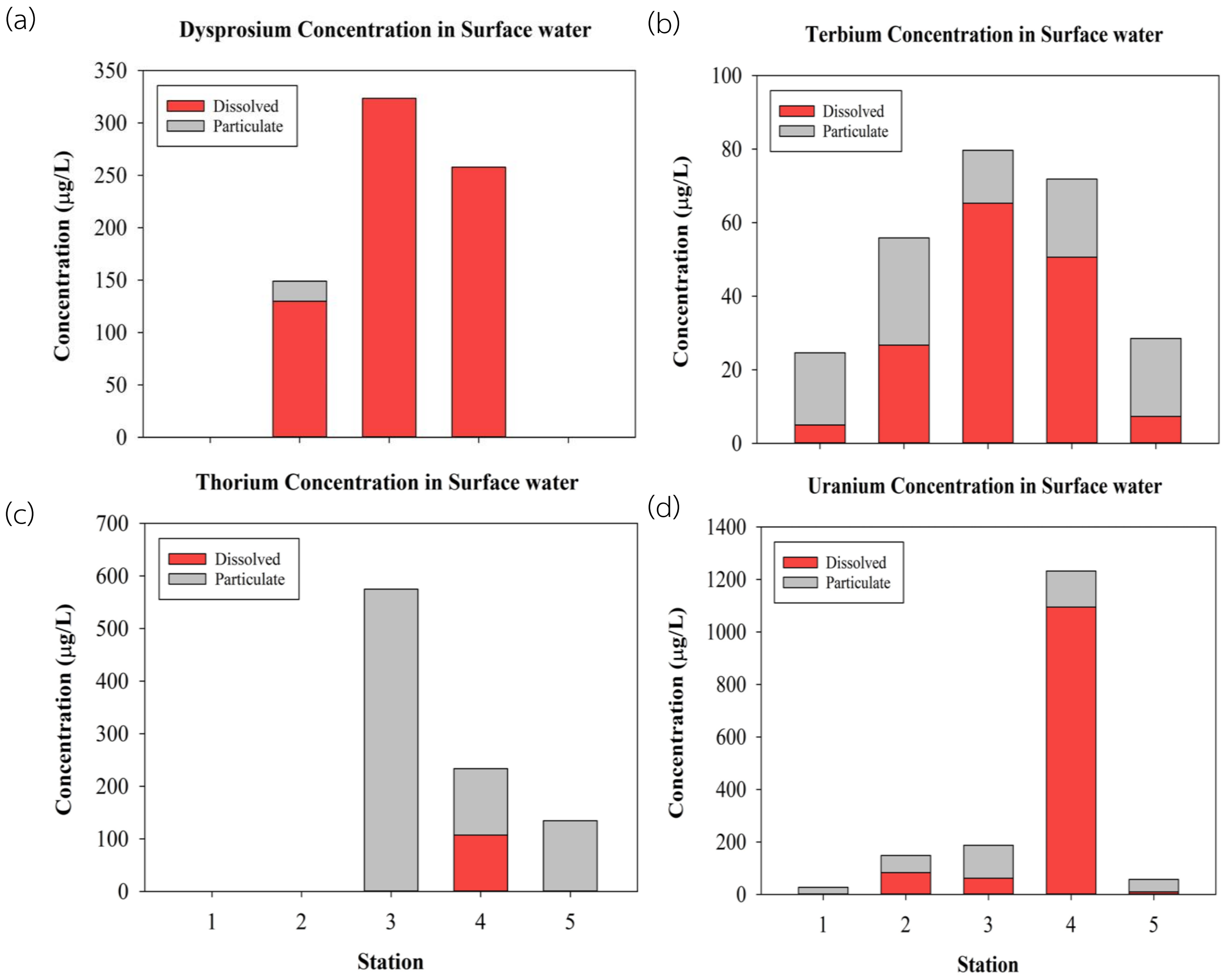
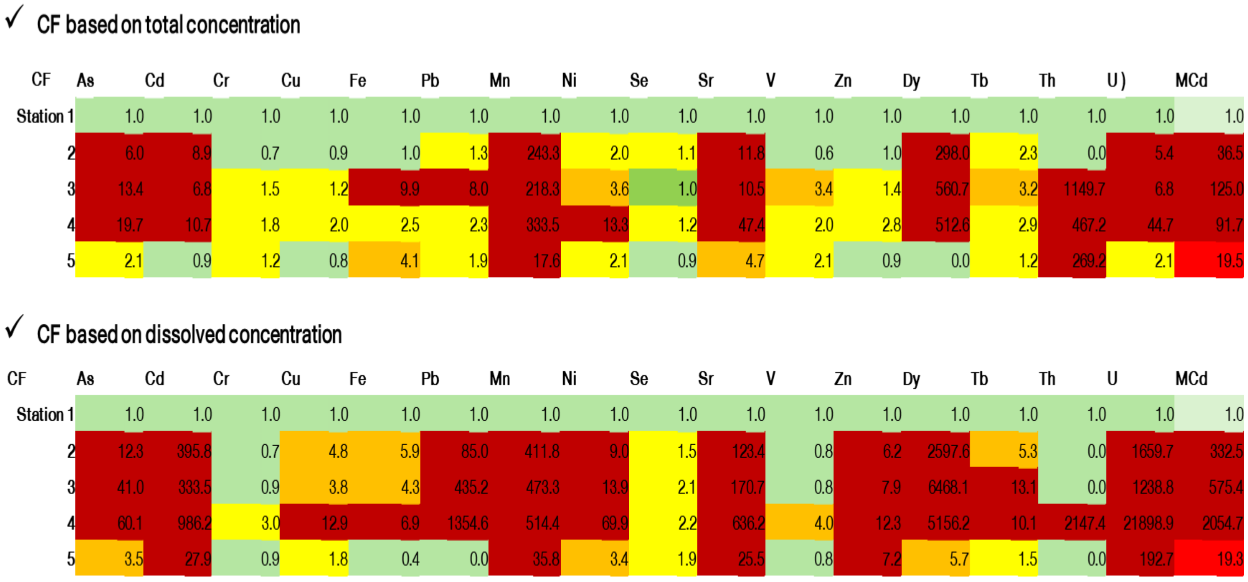


Figure 7 Dissolved and particulate concentrations of (a) Dy, (b) Tb, (c) Th, and (d) in water from Station 1 to 5



✓ CF based on total concentration

CF	As	Cd	Cr	Cu	Fe	Pb	Mn	Ni	Se	Sr	V	Zn	Dy	Tb	Th	U)	MCd
Station 1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	6.0	8.9	0.7	0.9	1.0	1.3	243.3	2.0	1.1	11.8	0.6	1.0	298.0	2.3	0.0	5.4	36.5
3	13.4	6.8	1.5	1.2	9.9	8.0	218.3	3.6	1.0	10.5	3.4	1.4	560.7	3.2	1149.7	6.8	125.0
4	19.7	10.7	1.8	2.0	2.5	2.3	333.5	13.3	1.2	47.4	2.0	2.8	512.6	2.9	467.2	44.7	91.7
5	2.1	0.9	1.2	0.8	4.1	1.9	17.6	2.1	0.9	4.7	2.1	0.9	0.0	1.2	269.2	2.1	19.5

✓ CF based on dissolved concentration

CF	As	Cd	Cr	Cu	Fe	Pb	Mn	Ni	Se	Sr	V	Zn	Dy	Tb	Th	U	MCd
Station 1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	12.3	395.8	0.7	4.8	5.9	85.0	411.8	9.0	1.5	123.4	0.8	6.2	2597.6	5.3	0.0	1659.7	332.5
3	41.0	333.5	0.9	3.8	4.3	435.2	473.3	13.9	2.1	170.7	0.8	7.9	6468.1	13.1	0.0	1238.8	575.4
4	60.1	986.2	3.0	12.9	6.9	1354.6	514.4	69.9	2.2	636.2	4.0	12.3	5156.2	10.1	2147.4	21898.9	2054.7
5	3.5	27.9	0.9	1.8	0.4	0.0	35.8	3.4	1.9	25.5	0.8	7.2	5.7	1.5	0.0	192.7	19.3

Figure 8 Visualization of CF and mCd based on the total and the dissolved concentrations of rare earth elements, radioactive elements, metals and metalloids in surface water samples from Station 1 to 5

Upstream Reference (Station 1):

In contrast, the upstream reference site (Station 1) showed minimal concentrations of REEs, radioactive elements, and toxic metals, representing the natural background levels in the area before the influence of mining activities.

Midstream and Downstream (Stations 3 and 5):

While Station 2 and 4 exhibited high concentrations of REES, radioactive species, metals, and metalloids, Station 3 (midstream) sometimes showed higher concentrations for some rare earth elements and metals, as illustrated in Figures 7 and 9. This pattern suggests that Station 3 may be receiving additional contamination inputs beyond those measured at Station 2, potentially from multiple mining operations in the area or from sediment re-suspension of previously deposited contaminants.

Importantly, the concentrations of certain toxic elements, including arsenic, cadmium, chromium, lead, and nickel, at Stations 2, 3, and 4 exceeded the World Health Organization (WHO) drinking water standards, posing potential health risks to the local population (WHO, 2017). These findings are consistent with previous studies that have reported elevated concentrations of rare earth elements, radioactive elements, and toxic metals in surface water near rare earth mining sites (Liu et al., 2018; Liu et al., 2021; Moldovan et al., 2022). The presence of these contaminants in surface water has been widely reported in the literature, with many studies highlighting the potential ecological and health risks associated with such contamination (Gwenzi et al., 2018; Fashola et al., 2016).

The spatial pattern of contamination observed in this study - with the highest levels in the leachate and direct discharge, decreasing concentrations downstream, and minimal contamination upstream - provides strong evidence for the impact of rare earth mining activities on local water quality. While natural attenuation processes may be occurring as contaminated water moves downstream, the effects of mining remain detectable for considerable distances from the source.

Our findings on water contamination levels are particularly significant when viewed in the context of China's new national standards for water pollution control from in-situ leaching of ionic rare earth mines, published in April 2024 (Appendix A.4). This first-of-its-kind national standard establishes control values for 11 pollutants at management control points, including pH (6-9), fluoride (1-2 mg/L), ammonia nitrogen (2 mg/L), and sulfate (500 mg/L). The severely contaminated water at Stations 2 and 4 far exceeds these newly established limits, with pH values of 3.65 and 3.30 respectively, and ammonia and sulfate concentrations orders of magnitude higher than permissible levels. Even Station 5, the furthest downstream point, shows contamination levels that would not meet these regulatory standards, underscoring the extensive reach of mining-related pollution. The Chinese standard also mandates comprehensive monitoring systems for both surface and groundwater, with specific requirements for monitoring frequency (weekly for key pollution control points), precisely the type of rigorous oversight our findings suggest is necessary in Myanmar.

These findings underscore the urgent need for stringent management of leachate and direct discharge from rare earth mining operations, coupled with comprehensive monitoring of downstream water quality. Such measures are crucial to protect aquatic ecosystems and human health in affected areas. Furthermore, the results highlight the importance of implementing effective water treatment solutions and educating local communities about the potential risks associated with using contaminated water sources, ensuring a holistic approach to mitigating the environmental and health impacts of rare earth mining activities.

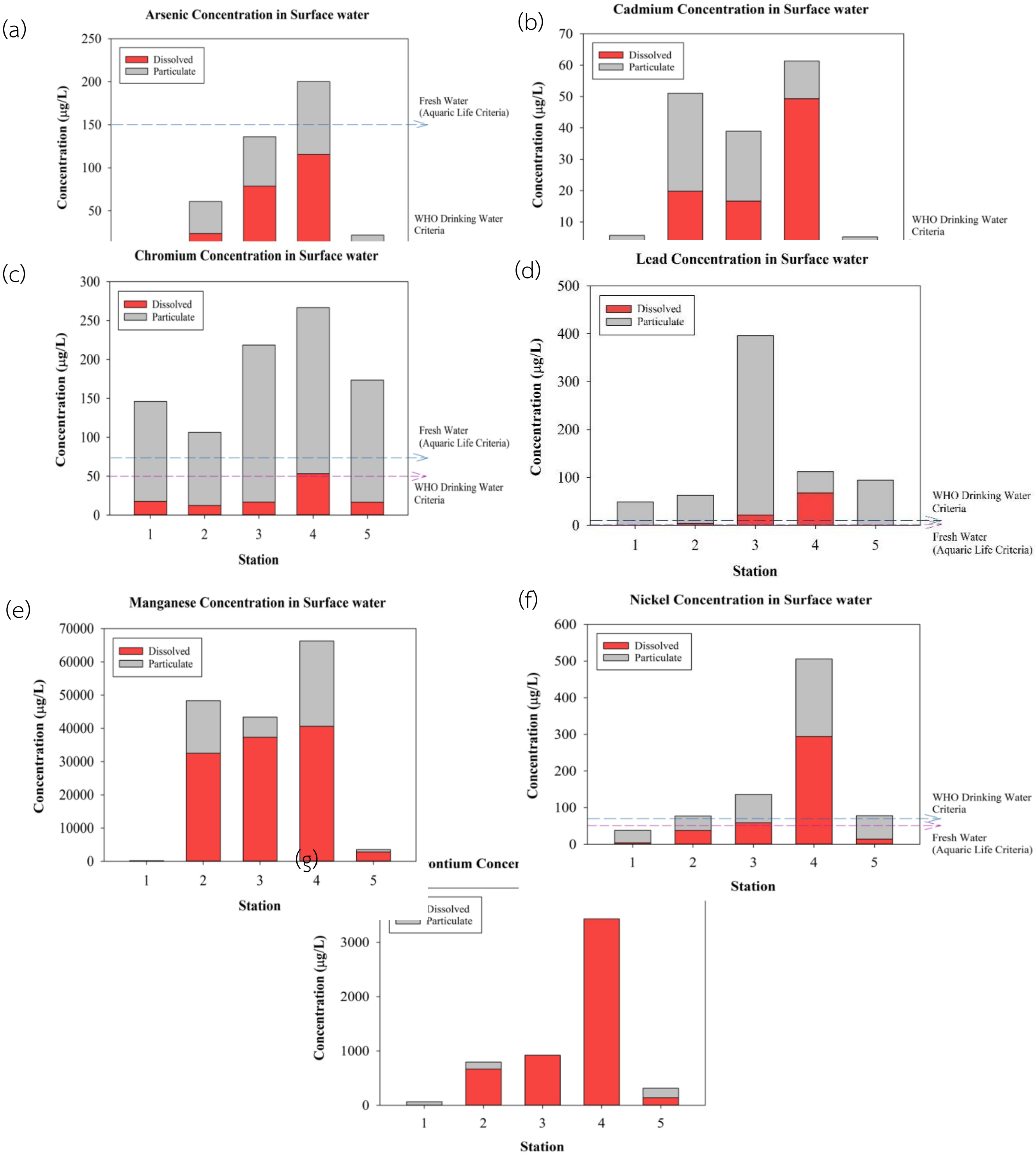
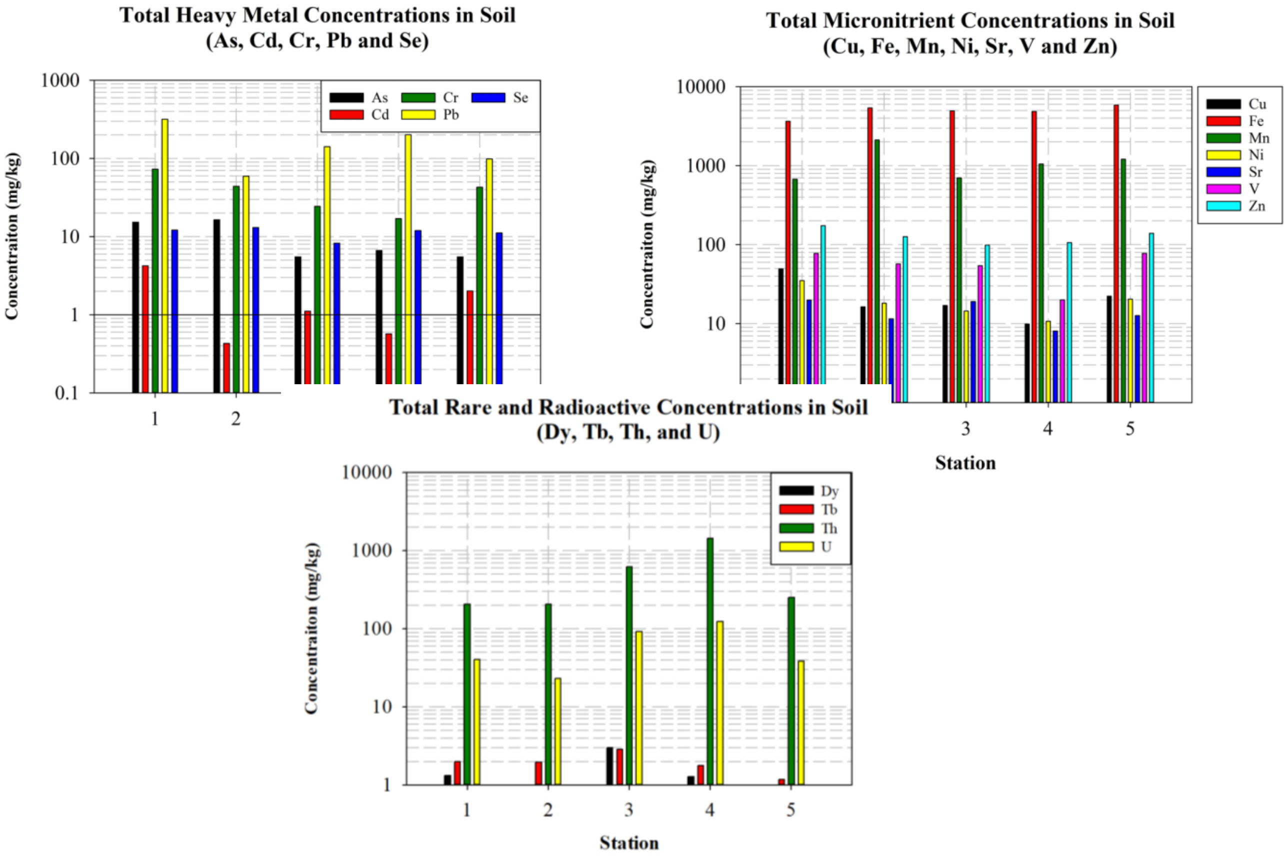


Figure 9 Dissolved and particulate concentrations of (a) arsenic, (b) cadmium, (c) chromium, and (d) lead, (e) manganese, (f) nickel, (g) strontium in water from Station 1 to 5

3.2 Soil contamination

The analysis of surface soil samples collected near the water sampling stations reveals minimal alterations in the concentrations of rare earth elements, metals, and metalloids, except for thorium and uranium. As depicted in Figure 10, the concentrations of most elements in surface soil at Stations 2, 3, and 4 are comparable to those at Stations 1 and 5, suggesting that the surface soil along the riverbank is not significantly affected by contamination from mine water. However, it is important to note that the potential contamination of deeper soil layers has not been investigated in this study (Jiang et al., 2019). This finding contrasts with some previous studies that have reported significant soil contamination near rare earth mining sites (Liu et al., 2018; Liu et al., 2021; Moldovan et al., 2022), highlighting the importance of site-specific factors in determining the extent of contamination.


Total Heavy Metal Concentrations in Soil (As, Cd, Cr, Pb and Se)

Total Micronitrient Concentrations in Soil (Cu, Fe, Mn, Ni, Sr, V and Zn)

Total Rare and Radioactive Concentrations in Soil (Dy, Tb, Th, and U)

Figure 10 Concentration of REEs, radioactive elements, metals, and metalloids in surface soil samples from Station 1 to 5

The sequential extraction of soil samples, as illustrated in Figure 11, confirms the absence of substantial anthropogenic contamination in surface soil. The mobile fractions (F1 and F2) of metals, metalloids, and rare earth elements in surface soil at Stations 2, 3, and 4 do not exhibit significant alterations compared to Stations 1 and 5. This finding, along with the total concentrations of these elements in surface soil, indicates that the surface soil has not been significantly impacted by anthropogenic contamination from rare earth mining activities (Filgueiras et al., 2002). Similar results have been reported in studies that have used sequential extraction to assess the potential mobility and bioavailability of contaminants in soils near mining sites (Anju & Banerjee, 2010; Li et al., 2019; Okoro et al., 2012). Notably, despite the high contamination levels observed in the water samples from Stations 2 (leachate from rare earth mining) and 4 (direct discharge from the mine to the sedimentation pond), the soil samples from these locations did not show significant contamination. This can be attributed to the fact that the contaminated water at these stations was directly discharged into the creek, as shown in Figure 4, rather than flowing over the soil surface as runoff. Consequently, the soil at these sites had minimal direct contact with the highly contaminated water, resulting in lower levels of soil contamination than might be expected given the water quality at these locations.

Lastly, the observed enrichment of Th and U in surface soil is likely of natural origin, as indicated by the sequential extraction results (Figure 10). The predominance of Th and U in the residual fraction (F5) suggests that their presence is primarily due to the natural composition of the soil rather than anthropogenic contamination (Ure et al., 1993). This finding is consistent with previous studies that have reported natural enrichment of Th and U in soils derived from specific parent materials (Sahoo et al., 2016; Yan et al., 2019; Pagano et al., 2019).

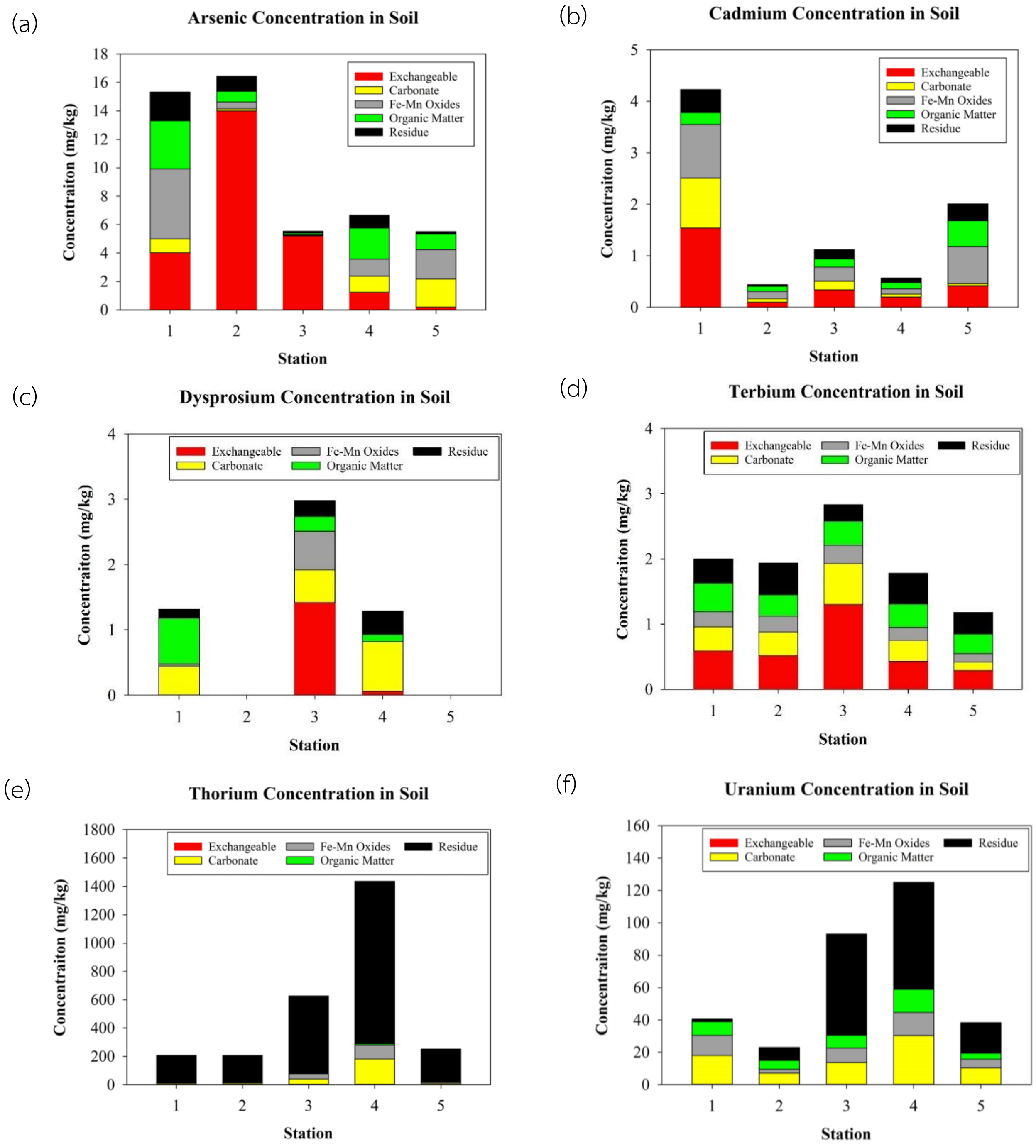


Figure 11 Sequential extraction results of (a) arsenic, (b) cadmium, (c) Dy, (d) Tb, (e) Th, and (f) U in surface soil samples from Station 1 to 5

3.3 Preliminary Impact Assessment

3.3.1 Water Resource for Human Use

The natural background condition at Station 1 has a WQI > 100 based on the total concentrations of contaminants (Figure 12), indicating that proper treatment is necessary before the water can be used for human consumption. However, when considering the dissolved concentrations, the WQI at Station 1 is 25, suggesting that simple filtration can improve the water quality to a level suitable for all intended human uses (Tiwari & Mishra, 1985). Similar findings have been reported in studies that have used WQI to assess the impact of mining activities on water resources (Wagh et al., 2018; Tian et al., 2019; Ewaid et al., 2018). In contrast, the mining activity significantly deteriorates the water quality at Stations 2, 3, and 4, with WQI values exceeding 5,000 based on total concentrations (Figure 12). Even when considering the dissolved concentrations, the WQI remains > 1,000 for these stations, confirming that filtration alone is insufficient to make the water suitable for drinking or fish culture. More advanced physicochemical treatment methods are required to restore the water quality for human use (Tyagi et al., 2013). The elements that contribute most to the poor water quality are manganese, lead, and cadmium. These findings are consistent with previous studies that have reported significant deterioration of water quality due to rare earth mining activities (Bozau et al., 2004; Hao et al., 2016; Siwe et al., 2015).

Furthermore, the downstream location at Station 5 experiences a significant deterioration in water quality compared to the upstream reference site at Station 1, highlighting the extensive impact of mining activities on downstream water resources (Bu et al., 2010). This finding underscores the importance of considering the spatial extent of contamination when assessing the environmental impact of mining activities (Pandey et al., 2016).

3.3.2 Water Resource for Aquatic Ecology

The Potential Ecological Risk Index (PERI) was employed to evaluate the risk posed by surface water contamination to aquatic ecology. As presented in Figure 12, the natural background condition at Station 1 shows mostly low to moderate contamination levels based on dissolved concentrations and moderate to considerable contamination levels based on total concentrations (Hakanson, 1980). This finding suggests that even in the absence of mining activities, the aquatic ecosystem may be subject to some level of stress due to naturally occurring contaminants (Masuda, 2018).

However, the mining activity increases the contamination levels at Stations 2, 3, and 4 to moderate to very high based on dissolved concentrations and considerably to highly contaminated based on total concentrations. All studied metalloids and metals, including arsenic, cadmium, chromium, lead, manganese, nickel, selenium, and zinc, exhibit contamination levels that pose potential risks to the aquatic ecosystem (Hakanson, 1980). The presence of cadmium, manganese, selenium, and zinc in the dissolved form enhances their bioavailability and potential toxicity to aquatic organisms (Luoma & Rainbow, 2008). These findings are consistent with previous studies that have reported significant ecological risks associated with rare earth mining activities (Wang et al., 2012; Liang et al., 2014; Zhuang et al., 2017).

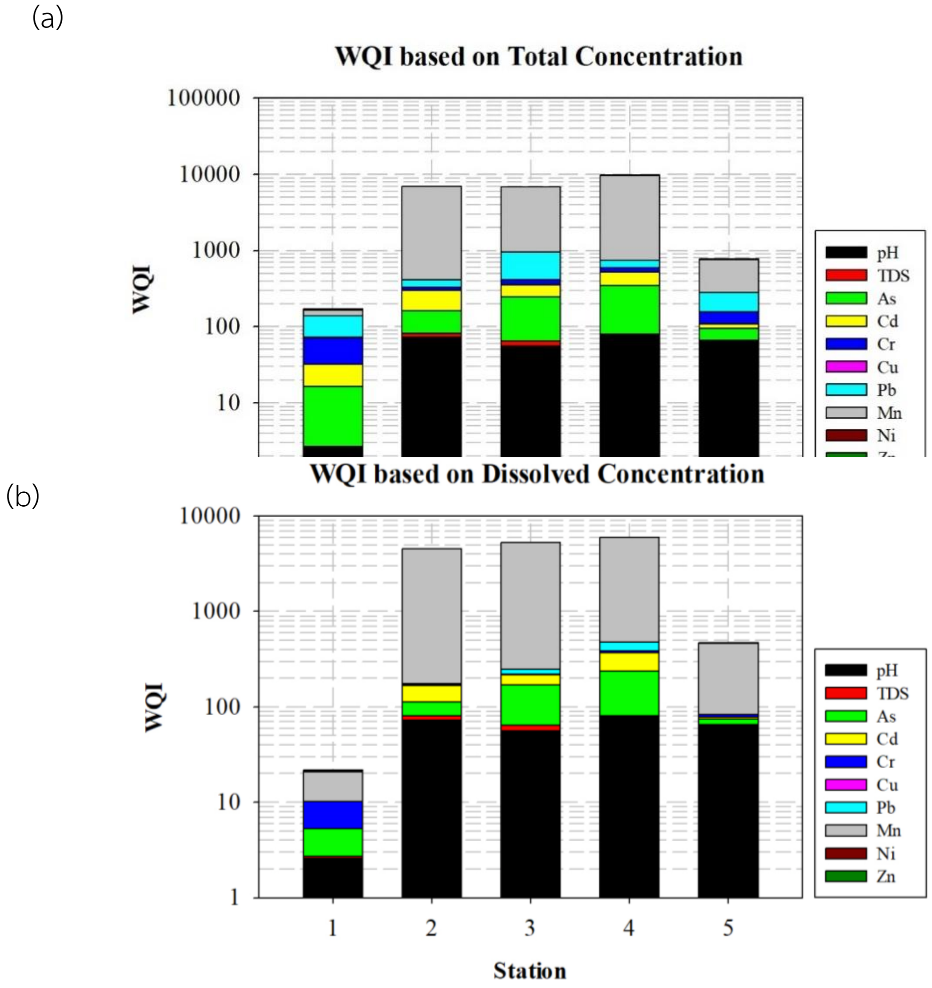
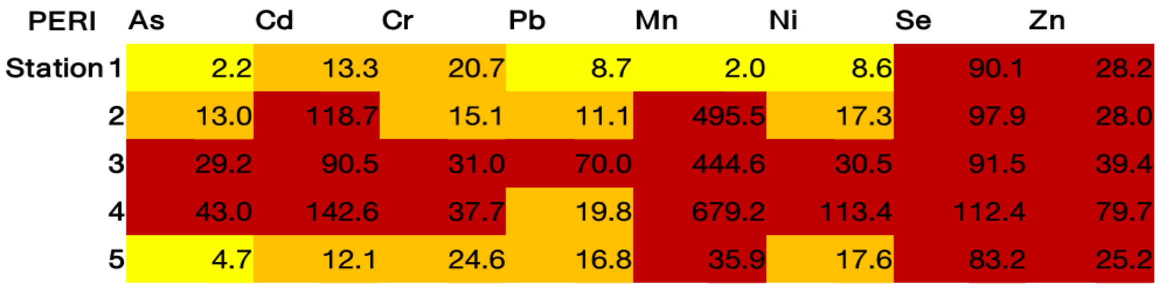


Figure 12 WQI of surface water from Station 1 to 5 based on (a) total concentration and (b) dissolved concentration

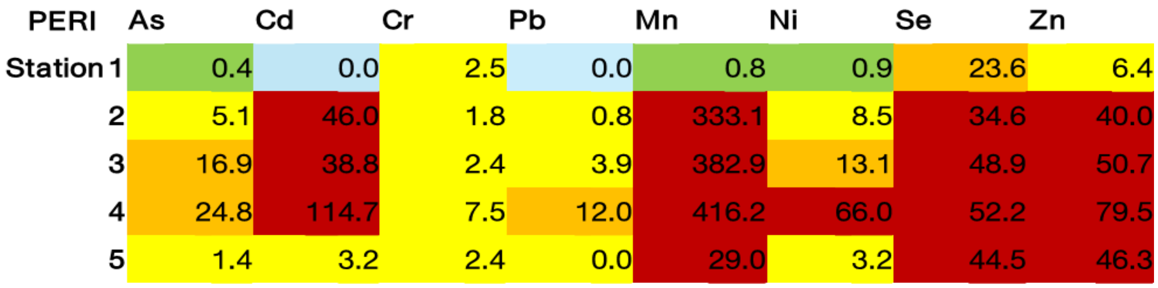
Regrettably, the downstream location at Station 5 experiences significantly higher ecological risks compared to the upstream reference site at Station 1, underscoring the detrimental impact of mining activities on the downstream aquatic environment (Liu et al., 2019). This finding highlights the need for comprehensive monitoring and management strategies to mitigate the ecological risks associated with rare earth mining (Ali, 2014; Kapustka et al., 2019).

✓ PERI based on total concentration



PERI	As	Cd	Cr	Pb	Mn	Ni	Se	Zn
Station 1	2.2	13.3	20.7	8.7	2.0	8.6	90.1	28.2
2	13.0	118.7	15.1	11.1	495.5	17.3	97.9	28.0
3	29.2	90.5	31.0	70.0	444.6	30.5	91.5	39.4
4	43.0	142.6	37.7	19.8	679.2	113.4	112.4	79.7
5	4.7	12.1	24.6	16.8	35.9	17.6	83.2	25.2

✓ PERI based on dissolved concentration



PERI	As	Cd	Cr	Pb	Mn	Ni	Se	Zn
Station 1	0.4	0.0	2.5	0.0	0.8	0.9	23.6	6.4
2	5.1	46.0	1.8	0.8	333.1	8.5	34.6	40.0
3	16.9	38.8	2.4	3.9	382.9	13.1	48.9	50.7
4	24.8	114.7	7.5	12.0	416.2	66.0	52.2	79.5
5	1.4	3.2	2.4	0.0	29.0	3.2	44.5	46.3

Figure 13 Visualization of PERI based on the total and the dissolved concentrations of metals and metalloids in surface water samples from Station 1 to 5

3.4 Contamination Hypothesis

The results of this study support Hypothesis 2, which posits that surface water contamination in the investigated area is caused by a combination of three primary pathways:

1. Subsurface migration of mine water through in-situ leaching
2. Drainage from high-elevation in-situ leaching sites to surface water
3. Direct discharge of mine water from the sedimentation pond to the creek

Evidence supporting this conclusion is twofold:

1. Significant surface water contamination: Stations 2 and 4, representing direct mine water, and Station 3, located in close proximity to the mining sites, exhibit highly elevated concentrations of ionic tracers, rare earth elements, radioactive elements, metals, and metalloids.
2. Minimal surface soil contamination: Surface soil near the river shows no substantial contamination, as indicated by minimal alterations in the concentrations and chemical fractions of rare earth elements, metals, and metalloids, except for the naturally occurring enrichment of thorium and uranium.

The juxtaposition of highly contaminated surface water with relatively uncontaminated surface soil suggests that the primary contamination pathways do not involve significant surface runoff from mining areas. Instead, the contamination likely occurs through subsurface migration, high-elevation drainage, or direct discharge to the creek (Zhao et al., 2012). This finding aligns with previous studies investigating the environmental impact of in-situ leaching techniques in rare earth mining (Yang et al., 2013; Liu et al., 2016; Jin et al., 2019; Zhang et al., 2021).

While Figure 4 provides evidence for drainage from high-elevation in-situ leaching sites and direct discharge from sedimentation ponds, the potential contribution of subsurface migration cannot be ruled out. To definitively confirm the extent of subsurface migration's contribution to creek contamination, further investigation, including deep soil sampling, is necessary.

3.5 Implications for Regulatory Framework Development

While China's recently published Water Pollution Control Standard for In-situ Leaching of Ionic Rare Earth Mines (April 2024) does not apply in Myanmar, international best practices and principles of corporate social responsibility suggest that companies should maintain the same environmental standards abroad as they do in their home countries (OECD, 2011; Mol, 2011; Compagnon & Alejandro, 2013). This "same company, same standards" principle has gained increasing recognition in international environmental governance, with organizations like the UN Global Compact advocating that multinational corporations should not exploit regulatory differences between countries (UN Global Compact, 2018).

Given that Chinese enterprises are the primary operators and beneficiaries of rare earth mining in Myanmar, and that Myanmar's rare earth resources are primarily exported to China (Global Witness, 2022), it is appropriate to use China's own standards as a benchmark for evaluating the environmental impacts we observed. With this framework in mind, our research team compared our findings against China's new national standard to provide context and highlight areas of concern.

Our water quality assessment results reveal contamination levels that substantially exceed the thresholds established in China's standard. For instance, at Stations 2 and 4, pH values (3.65 and 3.30) fall well below China's control point requirement of 6-9, while ammonia levels up to 29.8 times background would exceed even China's pollution monitoring point warning value of 30 mg/L. The chloride concentrations at Station 4 (reaching 238 times background levels) far surpass any acceptable limits in water quality standards.

The downstream impacts we observed at Stations 3 and 5 demonstrate the need for the type of comprehensive monitoring network mandated by the Chinese standard. Most concerning are the concentrations of dysprosium and terbium (up to 6,468 and 13.1 times background levels), and thorium and uranium (reaching 2,147 and 21,899 times background), which would trigger immediate regulatory action under China's framework.

Three key aspects of China's standard are particularly relevant for Myanmar based on our findings:

1. **Multi-tiered Monitoring System**: The Chinese standard establishes different monitoring points with varying threshold values: strict limits at management control points, early warning values at pollution monitoring points, and treatment facility discharge limits. Our findings support implementing a similar multi-tiered approach in Myanmar.
2. **Source Control Measures**: China's standard emphasizes source pollution reduction, including clean/wastewater separation and efficient leaching agent recovery. Our finding that the contamination pathway involves subsurface migration suggests that Myanmar's regulatory framework should prioritize subsurface leaching controls and groundwater protection measures.
3. **Emergency Response Mechanisms**: The persistent downstream contamination we detected underscores the need for end-of-pipe risk prevention measures similar to those required by China's standard, including emergency retention systems and groundwater pumping and treatment systems.

If Chinese mining companies were to apply the same standards in Myanmar as required in China, the current operations would necessitate immediate remedial action and significant improvements in pollution control systems. These improvements would align with global expectations for responsible business conduct in environmentally sensitive industries (UN Environment Programme, 2020).

The implementation of such frameworks would require significant investment in monitoring infrastructure and treatment technologies. However, the environmental and public health costs of inaction, as evidenced by our findings, suggest that applying these standards should be a priority for sustainable management of Myanmar's rare earth resources, regardless of different regulatory contexts between the two countries.

3.6 Remediation and Future Investigation Needed

This study clearly shows significant contamination of surface water in the creek by rare earth elements, radioactive elements, and toxic metals and metalloids. However, two key uncertainties remain that are critical for determining appropriate remediation approaches:

1. The extent of contamination in creek sediments

2. Whether there is ongoing subsurface migration of contaminants from in-situ leaching operations to the creek

Understanding these factors is crucial, as natural attenuation alone is likely insufficient for remediation, and engineered solutions will be necessary. For example, Phenrat et al. (2016) demonstrated that natural recovery of lead contamination in Klity Creek, Thailand would take 377 ± 76 years to reach background levels. Therefore, identifying the sources and environmental media requiring remediation is essential for developing an effective cleanup strategy.

If creek sediments are contaminated and the primary source is direct discharge of mine water, remediation could focus on treating the sediments once mining operations cease. Two main techniques for sediment remediation are:

- Sediment Dredging: Mechanical or hydraulic removal of contaminated sediments, followed by treatment and/or secure disposal. This physically removes contaminants from the aquatic environment.

- Sediment Capping: Placement of a layer of clean material (e.g. sand, gravel, geotextiles) over contaminated sediments to isolate them from the water column and biota. This can be enhanced with reactive materials to bind contaminants.

Estimated costs for sediment remediation based on previous projects are summarized in Table 9.

Table 9. Example costs for sediment remediation projects (State of the Strait Conference Report, 2022)

Project	Volume Remediated	Total Cost	Cost per m3
NWIRP Dallas, TX	274,000 m3	$40 million	$146
Hunters Point, CA	218,000 m3	$17 million	$78
Rouge River, MI	396,800 m3	$62.75 million	$158

However, if there is ongoing subsurface migration of contaminants from in-situ leaching operations directly to the creek, additional measures would be needed. One potential approach is installing a permeable reactive barrier (PRB) along the river bank to neutralize acidity and adsorb heavy metals before they enter the creek. PRBs are trenches filled with reactive materials (e.g. zero-valent iron, limestone) that passively treat contaminated groundwater as it flows through. They can be installed parallel to a creek to intercept and treat contaminated groundwater before it discharges to surface water. Estimated costs for PRB installations based on previous projects are provided in Table 10.

Table 10. Example costs for permeable reactive barrier installations

Project	PRB Length	Total Cost	Cost per meter
Ashtabula River, OH	335 m	$6.7 million	$20,000
Monticello, UT	520 m	$1.0 million	$1,900
Denver Federal Center, CO	520 m	$1.8 million	$3,500

The scale of contamination at rare earth mining sites can result in extremely high remediation costs. Table 11 summarizes remediation costs from several mine sites to illustrate the potential magnitude of expenses.

Table 11. Example remediation costs for contaminated mine sites (U.S. EPA, 1997)

Site	Contaminants	Remediation Cost
Summitville Mine, CO	Acid mine drainage, metals	$100 million
Bunker Hill, ID	Lead, zinc	$1.3 billion
Iron Mountain, CA	Acid mine drainage, metals	$1 billion
Tar Creek, OK	Lead, zinc	$540 million

Given these potentially enormous costs, additional site characterization is critical to design the most cost-effective remediation approach. Key investigations needed include:

1. Comprehensive sediment sampling and analysis throughout the creek to determine the full extent of contamination.

2. Installation of groundwater monitoring wells between in-situ leaching areas and the creek to evaluate subsurface contaminant migration.

3. Geophysical surveys to map potential preferential flow paths for contaminated groundwater.

4. Aquifer pumping tests to better characterize groundwater-surface water interactions.

5. Geochemical modeling to predict long-term contaminant fate and transport.

6. Ecological and human health risk assessments to prioritize areas for remediation.

7. Treatability studies to evaluate effectiveness of potential remediation technologies.

Based on the results of these investigations, a conceptual site model can be developed to guide remediation planning. Potential remediation components may include:

- Source control measures at in-situ leaching areas (e.g. hydraulic containment, grouting)
- Permeable reactive barriers along creek banks
- Sediment removal in highly contaminated areas
- Sediment capping in moderately contaminated areas
- Creek bank stabilization to prevent erosion of contaminated soils
- Surface water treatment system
- Monitored natural attenuation in less impacted areas
- Institutional controls to limit exposure (e.g. fish consumption advisories)

The investigations will help determine which combination of these approaches will be most effective. For example, if sediment contamination is limited, focus could be placed on source control and groundwater treatment. Conversely, if sediments are highly contaminated but groundwater inputs are minimal, emphasis could be on sediment removal/capping. Phased implementation may be appropriate, starting with source control and then progressing to sediment remediation once inputs are addressed. Adaptive site management should be employed, with remediation plans evolving based on monitoring results and cleanup progress.

Long-term monitoring will be crucial to evaluate remediation effectiveness and identify any needed adjustments. A robust monitoring program should include:

- Routine surface water and sediment sampling
- Groundwater monitoring
- Biomonitoring (e.g. fish tissue analysis)
- Habitat and ecological surveys

Community engagement throughout the remediation process is also essential. Local stakeholders should be involved in remediation planning and kept informed of progress. This can help address environmental justice concerns and ensure remediation efforts align with community needs and future land use plans.

While the potential costs are daunting, it's important to consider the long-term environmental, health, and economic benefits of remediation. Effective cleanup can:

- Reduce human and ecological health risks
- Restore ecosystem services
- Enable beneficial reuse of the site
- Improve property values
- Provide jobs and economic stimulus

Furthermore, the knowledge and technologies developed through rare earth mine remediation projects can advance the field of environmental restoration and potentially be applied to other contaminated sites globally.

In conclusion, while natural attenuation processes are occurring to some degree, the scale and complexity of contamination from rare earth mining operations necessitates engineered remediation approaches. Careful site characterization is needed to design the most effective and efficient cleanup strategy. Though remediation costs may be high, the long-term benefits to environmental and human health justify the investment. With proper planning and implementation, these contaminated sites can be transformed from environmental liabilities to community assets.

4. Conclusion

This study provides compelling evidence of significant environmental contamination resulting from rare earth mining activities in Kachin, Myanmar. Through comprehensive geochemical analyses and environmental forensics techniques, we have identified severe impacts on surface water quality, with implications for both ecological health and human well-being.

Key findings from our investigation include:

1. Severe contamination of surface water: Leachate from rare earth mining (Station 2) and direct discharge from the mine (Station 4) exhibited extremely acidic pH levels and alarmingly high concentrations of ionic species, rare earth elements (REEs), radioactive elements, and toxic metals and metalloids. These contaminant levels far exceeded those observed at the upstream reference site (Station 1).
2. Downstream impact: While contaminant concentrations decreased with distance from the source, significant pollution was still detected at the midstream (Station 3) and downstream (Station 5) sampling points, highlighting the extensive reach of mining-related contamination.
3. Minimal surface soil contamination: Contrary to expectations, surface soil samples showed little evidence of contamination, except for naturally occurring enrichment of thorium and uranium. This finding supports the hypothesis that contamination primarily occurs through subsurface migration, high-elevation drainage, or direct discharge to the creek, rather than surface runoff.
4. Severe degradation of water quality: Water Quality Index (WQI) calculations revealed that water from the contaminated sites is entirely unsuitable for human consumption, irrigation, or fish culture without extensive treatment. Even at the downstream location (Station 5), water quality remains significantly compromised compared to the upstream reference site.
5. High ecological risk: The Potential Ecological Risk Index (PERI) indicated that all studied metalloids and metals pose substantial risks to the aquatic ecosystem, with cadmium, manganese, selenium, and zinc presenting particularly high threats due to their presence in dissolved forms.

The recent publication of China's first national standard specifically addressing water pollution from in-situ leaching of ionic rare earth mines provides a valuable regulatory framework that could inform similar efforts in Myanmar. While our study reveals contamination levels in Myanmar that would substantially exceed China's new regulatory thresholds, the Chinese standard offers a practical model for developing regulatory approaches to manage the unique challenges posed by in-situ leaching operations. As China is the world's primary producer of rare earth elements and has decades of experience with their environmental impacts, adapting elements of this regulatory framework could accelerate Myanmar's path toward more sustainable rare earth mining practices.

In conclusion, this study reveals the severe environmental consequences of unregulated rare earth mining in Kachin, Myanmar. The findings highlight the critical need for balanced approaches that consider both the economic benefits of rare earth element production and the imperative of environmental protection and public health. As global demand for rare earth elements continues to grow, it is crucial that mining practices evolve to minimize environmental impacts and ensure the long-term sustainability of both the industry and the ecosystems it affects. The situation in Myanmar serves as a stark reminder of the potential costs of unchecked resource extraction and underscores the urgent need for responsible mining practices, stringent environmental regulations, and comprehensive remediation efforts in areas affected by rare earth mining activities.

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Appendix

Appendix A.1: Sample Collection Steps

Water and Soil Sample Collection Guidelines

This appendix outlines the procedures for collecting water and soil samples for laboratory analysis. For accurate results, please follow these guidelines carefully.

1. General Recommendations

If ice preservation is not possible, samples should be delivered to the analysis center within 2 days, and not exceeding 7 days after collection.

2. Equipment Required

Water Sampling Kit:

- Plastic bottles (600 mL) - 2 bottles
- HDPE bottles (1L) - 1 bottle
- HDPE bottles (500 mL) - 1 bottle
- pH test strips/kit
- Plastic funnel
- Sulfuric acid (H_2SO_4)
- Nitric acid (HNO_3)
- Rubber gloves
- Sample collection bucket
- Cooler box with ice (for sample preservation)

Soil Sampling Kit:

- Spade/shovel
- Cloth gloves
- Plastic bags
- Zipper top bags for soil samples
- Marker for labeling

3. Please visit the website or scan the QR code below

Website	QR code
https://drive.google.com/file/d/1i694UY18S9Z9aZcWrqLuryp2jnTz1B5a/view	

4. Site Selection Criteria

Sampling locations should be divided into three categories:

1. **Impacted Areas** (3 locations): Areas with evidence of human activity such as mining operations, drilling, smelting, waste deposits, or environmental indicators like gold-colored particles, white/red salt crust, mine tailings, or acidic blue water.
2. **Potentially Impacted Areas** (1 location): Areas that may have received impact from human activities.
3. **Background/Control Area** (1 location): Upstream area representing unimpacted conditions.

5. Water Sample Collection Procedure

1. Survey and select appropriate sampling location.
2. Record GPS coordinates of the sampling site.
3. Put on rubber gloves before handling samples.
4. Prepare sample bottles:
    - For 1L HDPE bottle: Add 2 mL of H_2SO_4
    - For 500 mL HDPE bottle: Add 1 mL of HNO_3
5. Rinse the collection bucket and funnel with water from the sampling site.
6. Collect water from approximately 20 cm below the surface and test pH using test strips.
7. Record pH value and take a photograph of the test strip for documentation.
8. Collect water from 20 cm below the surface and fill bottles completely (no air space):

   - Two 600 mL plastic bottles (no acid preservation)
   - One 1L HDPE bottle (with H_2SO_4)
   - One 500 mL HDPE bottle (with HNO_3)

9. Secure caps tightly to prevent leakage during transport.
10. Alternative method: If more convenient, collect five 600 mL bottles of water on-site, then transfer to acid-preserved bottles upon return.

6. Soil Sample Collection Procedure

1. After completing water sampling, proceed to soil collection.
2. Put on cloth gloves.
3. Clear surface debris from soil sampling area.
4. Use spade to dig to a depth of 15 cm.
5. Collect soil from 4 different holes within the sampling area.
6. Place soil samples on a plastic sheet and thoroughly mix.
7. Divide the mixed soil into 4 portions.
8. Select one portion and collect approximately 200 grams in a zipper bag.
9. Seal the bag tightly to prevent contamination and moisture intrusion.

7. Sample Preservation and Transport

1. Place all samples in the cooler box.
2. Fill cooler box with ice (if ice is unavailable, deliver samples within 7 days).
3. Seal the cooler box and attach sample information records.
4. Take photographs of the samples and forms for documentation.
5. Transport samples to the analytical laboratory with the completed documentation.

8. Required Sample Volumes and Preservation Methods

Parameters for Analysis	Container Type	Sample Volume Required for Analysis (2 replicates) (ml)	Preservation Method	Maximum Recommended Holding Time	Allowable Holding Time
1. pH	P, G	-	Analyze immediately at the site	0.25 hours	0.25 hours
2. Nitrite	P, G	20	Analyze immediately or refrigerate at 4-10 °C	None	48 hours
3. Fluoride	P, G	200	Store at room temperature	28 days	28 days
4. Chloride	P, G	100	Store at room temperature	N.S.	28 days
5. Sulfate	P, G	200	Refrigerate at 4-10 °C	28 days	28 days
6. Ammonia	P, G	500	Analyze immediately or refrigerate at 4-10 °C after adding H_2SO_4 to pH < 2	7 days	28 days

Parameters for Analysis	**Container Type**	**Sample Volume Required for Analysis (2 replicates) (ml)**	**Preservation Method**	**Maximum Recommended Holding Time**	**Allowable Holding Time**
7. TDS	P, G	500	Refrigerate at 4-10 °C	7 days	-
8. Total alkalinity	P, G	100	Refrigerate at 4-10 °C	24 hours	14 days
9. Zn	P(A), G(A)	25	Add HNO_3 to pH < 2	6 months	6 months
10. Cu	P(A), G(A)	25	Add HNO_3 to pH < 2	6 months	6 months
11. Ni	P(A), G(A)	25	Add HNO_3 to pH < 2	6 months	6 months
12. V	P(A), G(A)	25	Add HNO_3 to pH < 2	6 months	6 months
13. Cr	P(A), G(A)	25	Add HNO_3 to pH < 2	6 months	6 months
14. Se	P(A), G(A)	25	Add HNO_3 to pH < 2	6 months	6 months

Parameters for Analysis	**Container Type**	**Sample Volume Required for Analysis (2 replicates) (ml)**	**Preservation Method**	**Maximum Recommended Holding Time**	**Allowable Holding Time**
15. Sr	P(A), G(A), (HDPE) wrapped in foil	25	Filter immediately then add HNO_3 to pH < 2 (no air space), refrigerate at 4-10 °C	6 months	6 months
16. Co	P(A), G(A)	25	Add HNO_3 to pH < 2	6 months	6 months
17. Cadmium	P(A), G(A)	25	Add HNO_3 to pH < 2	6 months	6 months
18. Lead	P(A), G(A)	25	Add HNO_3 to pH < 2	6 months	6 months
19. Mn	P(A), G(A)	25	Add HNO_3 to pH < 2	6 months	6 months

Parameters for Analysis	Container Type	Sample Volume Required for Analysis (2 replicates) (ml)	Preservation Method	Maximum Recommended Holding Time	Allowable Holding Time
20. As	P(A), G(A)	25	Filter immediately then add HNO_3 to pH < 2	6 months	6 months
21. Iron	P(A), G(A)	25	Filter immediately then add HNO_3 to pH < 2	6 months	6 months
22. Thorium	P(A), G(A), (HDPE) wrapped in foil	25	Filter immediately then add HNO_3 to pH < 2 (no air space), refrigerate at 4-10 °C	6 months	6 months

Parameters for Analysis	**Container Type**	**Sample Volume Required for Analysis (2 replicates) (ml)**	**Preservation Method**	**Maximum Recommended Holding Time**	**Allowable Holding Time**
23. Uranium	P(A), G(A), (HDPE) wrapped in foil	25	Filter immediately then add HNO_3 to pH < 2 (no air space), refrigerate at 4-10 °C	6 months	6 months
24. Dysprosium	P(A), G(A), (HDPE) wrapped in foil	25	Filter immediately then add HNO_3 to pH < 2 (no air space), refrigerate at 4-10 °C	6 months	6 months

Parameters for Analysis	**Container Type**	**Sample Volume Required for Analysis (2 replicates) (ml)**	**Preservation Method**	**Maximum Recommended Holding Time**	**Allowable Holding Time**
25. Terbium	P(A), G(A), (HDPE) wrapped in foil	25	Filter immediately then add HNO_3 to pH < 2 (no air space), refrigerate at 4-10 °C	6 months	6 months
26. Soil sample		200 grams			
Total		**2045**			

Note: P = Plastic (polyethylene or equivalent) G = Glass HDPE = HDPE plastic bottle P(A), G(A) = Washed with nitric acid mixed with water (1:1) N.S. = Not specified in reference documents

Appendix A.2: Sample Images of Water and Soil Specimens

This appendix provides visual examples of water and soil samples collected following the procedures described in Appendix A.1. The images serve as reference guides for sample characteristics and proper storage methods.

A.2.1 Soil Sample Collection

Figure A.2.1: Various soil samples collected from different locations, properly stored in sealed plastic bags with identification labels. The samples show different soil colorations and textures, ranging from light brown to dark gray, representing various sampling locations and soil compositions.

A.2.2 Sample Storage and Transportation

Figure A.2.2: Sample storage in a foam cooler for transportation. This cooler is used to refrigerate samples to preserve their integrity during transport from field to laboratory. Information is written on the cooler to prevent confusion. Maintaining samples at low temperatures helps slow down chemical and biological reactions that may affect sample quality.

A.2.3 Water Sample Collection

Figure A.2.3: Water samples collected in sealed plastic bags with proper identification. The transparent bags allow for visual inspection of water clarity while maintaining sample integrity. These samples are ready for laboratory analysis of various parameters including pH, dissolved minerals, and potential contaminants.

Note: All samples were collected according to standard protocols described in Appendix A.1. Proper labeling, sealing, and storage techniques are essential for maintaining sample integrity and ensuring reliable analytical results.

Appendix A.3: Results of soil-water sample analysis from Myanmar

Water samples

Sample name	Temp (^oC)	pH	ORP (mV)	TDS (mg/L)	SAL (ppt)	EC (µS/cm)	TSS (g/L)
DI water	32.5	5.91	55	1.15	0.01	2.04	0
1	24	6.88	-4	9.58	0.02	20.5	0
2	23	3.65	186	811	0.83	1539	0.01
3	28.2	4.41	141	781	0.79	1549	2.6725
4	26.5	3.3	210	3.91	4.32	7.88	0.135
5	27	4	166	63.4	0.07	129	1.06

Heavy metal types	**Sample name**	**As (µg/L)**	**Cd (µg/L)**	**Cr (µg/L)**	**Cu (µg/L)**	**Fe (µg/L)**	**Pb (µg/L)**	**Mn (µg/L)**	**Ni (µg/L)**	**Se (µg/L)**	**Sr (µg/L)**	**V (µg/L)**	**Zn (µg/L)**	**Dy (µg/L)**	**Tb (µg/L)**	**Th (µg/L)**	**U (µg/L)**	**F (mg/L)**	**Cl^- (mg/L)**	**NO_2^- (mg/L)**	**NH_3 (mg/L)**
Mobile heavy metals in water	1	1.92	0.05	17.73	9.18	79.36	0.05	78.93	4.21	206.43	5.39	5.14	165.18	0.05	5.00	0.05	0.05	0	0	0	0
	2	23.66	19.79	12.41	43.65	471.33	4.25	32501.66	37.78	303.27	665.80	4.05	1025.59	129.88	26.71	0.00	82.98	0	0	0	0
	3	78.78	16.68	16.77	34.59	341.86	21.76	37356.23	58.55	428.24	920.71	4.30	1299.15	323.41	65.29	0.00	61.94	0	0	0	0
	4	115.62	49.31	53.20	118.18	550.07	67.73	40604.52	294.36	457.57	3431.96	20.55	2037.52	257.81	50.65	107.37	1094.94	0	0	0	0
	5	6.65	1.40	16.64	16.60	31.51	0.00	2828.40	14.24	389.97	137.57	4.10	1188.38	0.28	7.32	0.00	9.63	0	0	0	0
Total heavy metals in water	1	10.15	5.73	146.13	124.92	1069.10	49.26	198.70	38.15	789.40	67.22	43.72	722.47	0.50	24.59	0.50	27.59	0.05	0.50	0.00	0.17
	2	60.73	51.03	106.36	107.13	1101.86	62.99	48341.68	77.28	857.41	794.68	28.34	716.78	149.00	55.88	0.00	148.52	0.86	12.50	0.00	35.50
	3	136.08	38.92	218.56	149.08	10631.78	395.54	43378.66	136.19	801.98	704.58	146.66	1009.06	280.36	79.68	574.87	187.36	0.27	10.00	0.00	68.10
	4	200.16	61.30	266.50	246.41	2636.16	112.14	66267.47	505.73	985.01	3184.66	89.16	2042.84	256.32	71.83	233.58	1232.32	1.49	119.00	0.00	187.00
	5	21.78	5.21	173.49	97.66	4408.84	94.81	3504.12	78.32	728.90	313.44	91.96	646.16	0.00	28.54	134.61	57.37	0.64	0.50	0.00	1.62

Total

PERI	As	Cd	Cr	Pb	Mn	Ni	Se	Zn
1	2.2	13.3	20.7	8.7	2.0	8.6	90.1	28.2
2	13.0	118.7	15.1	11.1	495.5	17.3	97.9	28.0
3	29.2	90.5	31.0	70.0	444.6	30.5	91.5	39.4
4	43.0	142.6	37.7	19.8	679.2	113.4	112.4	79.7
5	4.7	12.1	24.6	16.8	35.9	17.6	83.2	25.2

Dissolved

PERI	As	Cd	Cr	Pb	Mn	Ni	Se	Zn
1	0.4	0.0	2.5	0.0	0.8	0.9	23.6	6.4
2	5.1	46.0	1.8	0.8	333.1	8.5	34.6	40.0
3	16.9	38.8	2.4	3.9	382.9	13.1	48.9	50.7
4	24.8	114.7	7.5	12.0	416.2	66.0	52.2	79.5
5	1.4	3.2	2.4	0.0	29.0	3.2	44.5	46.3

Total

CF	As (µg/L)	Cd (µg/L)	Cr (µg/L)	Cu (µg/L)	Fe (µg/L)	Pb (µg/L)	Mn (µg/L)	Ni (µg/L)	Se (µg/L)	Sr (µg/L)	V (µg/L)	Zn (µg/L)	Dy (µg/L)	Tb (µg/L)	Th (µg/L)	U (µg/L)	MCd
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	6.0	8.9	0.7	0.9	1.0	1.3	243.3	2.0	1.1	11.8	0.6	1.0	298.0	2.3	0.0	5.4	36.5
3	13.4	6.8	1.5	1.2	9.9	8.0	218.3	3.6	1.0	10.5	3.4	1.4	560.7	3.2	1149.7	6.8	125.0
4	19.7	10.7	1.8	2.0	2.5	2.3	333.5	13.3	1.2	47.4	2.0	2.8	512.6	2.9	467.2	44.7	91.7
5	2.1	0.9	1.2	0.8	4.1	1.9	17.6	2.1	0.9	4.7	2.1	0.9	0.0	1.2	269.2	2.1	19.5

Dissolved

CF	As (µg/L)	Cd (µg/L)	Cr (µg/L)	Cu (µg/L)	Fe (µg/L)	Pb (µg/L)	Mn (µg/L)	Ni (µg/L)	Se (µg/L)	Sr (µg/L)	V (µg/L)	Zn (µg/L)	Dy (µg/L)	Tb (µg/L)	Th (µg/L)	U (µg/L)	MCd
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	12.3	395.8	0.7	4.8	5.9	85.0	411.8	9.0	1.5	123.4	0.8	6.2	2597.6	5.3	0.0	1659.7	332.5
3	41.0	333.5	0.9	3.8	4.3	435.2	473.3	13.9	2.1	170.7	0.8	7.9	6468.1	13.1	0.0	1238.8	575.4
4	60.1	986.2	3.0	12.9	6.9	1354.6	514.4	69.9	2.2	636.2	4.0	12.3	5156.2	10.1	2147.4	21898.9	2054.7
5	3.5	27.9	0.9	1.8	0.4	0.0	35.8	3.4	1.9	25.5	0.8	7.2	5.7	1.5	0.0	192.7	19.3

Soil samples

Sample name	pH	ORP (mV)	TDS (mg/L)	SAL (ppt)	EC (µS/cm)
1	4.98	132	131.1	0.13	2.58E+02
2	5.39	102	45.2	0.05	91.1
3	4.46	166	377	0.36	760
4	5.54	96	31.5	0.04	62.1
5	5.62	91	50.3	0.05	100.7

Total heavy metals in soil

Sample name	As (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Pb (mg/kg)	Mn (mg/kg)	Ni (mg/kg)	Se (mg/kg)	Sr (mg/kg)	V (mg/kg)	Zn (mg/kg)	Dy (mg/kg)	Tb (mg/kg)	Th (mg/kg)	U (mg/kg)
1	15.32	4.23	73.03	49.39	3641.68	317.15	675.41	35.08	12.18	19.84	77.59	173.81	1.32	2.00	207.60	40.72
2	16.44	0.43	44.11	16.32	5380.52	59.50	2116.37	18.10	13.09	11.51	57.09	126.47	0.00	1.94	206.63	22.99
3	5.53	1.11	24.45	16.93	4949.83	141.44	699.43	14.42	8.25	19.01	54.28	98.89	2.98	2.83	626.78	93.09
4	6.66	0.57	17.01	9.92	4860.18	200.57	1048.97	10.71	11.96	8.04	19.98	106.63	1.28	1.77	1435.89	125.05
5	5.51	2.01	42.93	22.30	5872.79	98.48	1205.77	20.45	11.16	12.67	77.68	139.30	0.00	1.18	251.54	38.33

Fractions of heavy metals in soil

Sample name	Fractions	As (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Pb (mg/kg)	Mn (mg/kg)	Ni (mg/kg)	Se (mg/kg)	Sr (mg/kg)	V (mg/kg)	Zn (mg/kg)	Dy (mg/kg)	Tb (mg/kg)	Th (mg/kg)	U (mg/kg)
1	Exchangeable	4.02	1.54	3.13	7.75	204.72	89.65	268.64	16.22	3.23	17.43	39.44	59.88	0.00	0.59	0.00	0.00
	Carbonate	0.97	0.97	8.14	2.72	186.46	91.92	158.08	2.95	2.05	1.32	3.24	30.22	0.45	0.37	10.32	18.03
	Fe-Mn oxides	4.93	1.04	29.32	9.62	2017.50	60.55	108.19	6.98	1.43	0.33	12.34	40.00	0.03	0.23	4.70	12.42
	Organical	3.38	0.23	11.66	20.37	941.03	31.01	42.70	6.71	3.40	0.17	12.86	30.33	0.70	0.44	5.06	8.41
	Residue	2.02	0.45	20.78	8.93	291.98	44.02	97.80	2.22	2.07	0.59	9.71	13.38	0.14	0.37	187.53	1.86
2	Exchangeable	14.00	0.10	2.43	6.54	4.32	16.33	206.23	9.25	3.13	9.76	35.32	25.03	0.00	0.52	0.05	0.00
	Carbonate	0.14	0.07	3.25	1.22	37.06	15.32	260.99	0.43	4.78	0.56	1.10	6.72	0.00	0.36	10.93	7.11
	Fe-Mn oxides	0.48	0.14	23.01	1.89	1007.09	12.48	1089.71	2.89	1.04	0.21	7.60	30.59	0.00	0.24	5.54	2.40
	Organical	0.76	0.10	12.27	3.09	211.01	13.11	532.23	4.79	3.25	0.27	8.70	50.13	0.00	0.33	0.43	5.48
	Residue	1.06	0.03	3.15	3.58	4121.04	2.26	27.21	0.74	0.89	0.71	4.37	14.00	0.00	0.49	189.68	8.00
3	Exchangeable	5.21	0.34	1.37	5.12	3.96	36.69	164.41	9.64	2.56	14.90	33.13	20.01	1.42	1.30	0.47	0.02
	Carbonate	0.04	0.17	1.04	2.85	6.47	22.57	31.69	0.17	2.48	1.42	0.45	1.17	0.50	0.63	40.28	13.70
	Fe-Mn oxides	0.05	0.27	10.67	1.85	351.59	37.42	235.19	1.13	0.69	0.53	4.53	7.68	0.59	0.28	37.38	8.88
	Organical	0.10	0.16	9.44	3.04	66.22	18.77	214.13	3.08	1.52	0.86	13.97	45.62	0.23	0.37	2.27	7.90
	Residue	0.14	0.18	1.93	4.06	4521.59	25.99	54.00	0.40	0.99	1.30	2.20	24.41	0.24	0.25	546.38	62.60
4	Exchangeable	1.23	0.20	2.89	2.51	5.03	34.43	234.12	6.60	1.55	5.79	12.10	23.99	0.06	0.43	1.91	0.02
	Carbonate	1.14	0.06	1.57	3.73	62.03	70.00	156.69	0.12	5.27	0.89	0.20	4.34	0.76	0.32	179.62	30.36
	Fe-Mn oxides	1.20	0.10	8.21	0.97	972.28	60.20	404.23	1.23	1.85	0.38	2.31	26.50	0.00	0.20	97.23	14.18
	Organical	2.19	0.12	1.80	1.99	177.50	24.54	153.23	1.40	1.31	0.64	1.83	42.12	0.11	0.36	9.25	14.32
	Residue	0.90	0.09	2.54	0.72	3643.34	11.40	100.70	1.36	1.98	0.35	3.54	9.68	0.36	0.47	1147.89	66.17

Sample name	Fractions	As (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Pb (mg/kg)	Mn (mg/kg)	Ni (mg/kg)	Se (mg/kg)	Sr (mg/kg)	V (mg/kg)	Zn (mg/kg)	Dy (mg/kg)	Tb (mg/kg)	Th (mg/kg)	U (mg/kg)
5	Exchangeable	0.20	0.42	1.89	4.32	5.50	7.54	160.07	10.43	1.21	10.23	42.66	21.33	0.00	0.29	0.00	0.00
	Carbonate	1.98	0.04	2.27	8.09	27.94	28.39	170.64	0.70	7.12	0.63	1.55	9.53	0.00	0.13	9.97	10.29
	Fe-Mn oxides	2.06	0.72	23.80	2.43	731.76	37.77	534.17	1.49	0.69	0.39	13.67	31.85	0.00	0.13	8.61	5.42
	Organical	1.10	0.50	11.24	4.11	187.06	13.25	223.88	3.79	1.04	1.03	16.57	72.70	0.00	0.30	0.14	3.76
	Residue	0.17	0.33	3.73	3.35	4920.54	11.54	117.01	4.04	1.10	0.39	3.24	3.89	0.00	0.33	232.82	18.86

1						2					3					4					5				
Fractions	**Exchangeable**	**Carbonate**	**Fe-Mn oxides**	**Organical**	**Residue**	**Exchangeable**	**Carbonate**	**Fe-Mn oxides**	**Organical**	**Residue**	**Exchangeable**	**Carbonate**	**Fe-Mn oxides**	**Organical**	**Residue**	**Exchangeable**	**Carbonate**	**Fe-Mn oxides**	**Organical**	**Residue**	**Exchangeable**	**Carbonate**	**Fe-Mn oxides**	**Organical**	**Residue**
As (mg/kg)	4.02	0.97	4.93	3.38	2.02	14.00	0.14	0.48	0.76	1.06	5.21	0.04	0.05	0.10	0.14	1.23	1.14	1.20	2.19	0.90	0.20	1.98	2.06	1.10	0.17
Cd (mg/kg)	1.54	0.97	1.04	0.23	0.45	0.10	0.07	0.14	0.10	0.03	0.34	0.17	0.27	0.16	0.18	0.20	0.06	0.10	0.12	0.09	0.42	0.04	0.72	0.50	0.33
Cr (mg/kg)	3.13	8.14	29.32	11.66	20.78	2.43	3.25	23.01	12.27	3.15	1.37	1.04	10.67	9.44	1.93	2.89	1.57	8.21	1.80	2.54	1.89	2.27	23.80	11.24	3.73
Cu (mg/kg)	7.75	2.72	9.62	20.37	8.93	6.54	1.22	1.89	3.09	3.58	5.12	2.85	1.85	3.04	4.06	2.51	3.73	0.97	1.99	0.72	4.32	8.09	2.43	4.11	3.35
Fe (mg/kg)	204.72	186.46	2017.50	941.03	291.98	4.32	37.06	1007.09	211.01	4121.04	3.96	6.47	351.59	66.22	4521.59	5.03	62.03	972.28	177.50	3643.34	5.50	27.94	731.76	187.06	4920.54
Pb (mg/kg)	89.65	91.92	60.55	31.01	44.02	16.33	15.32	12.48	13.11	2.26	36.69	22.57	37.42	18.77	25.99	34.43	70.00	60.20	24.54	11.40	7.54	28.39	37.77	13.25	11.54
Mn (mg/kg)	268.64	158.08	108.19	42.70	97.80	206.23	260.99	1089.71	532.23	27.21	164.41	31.69	235.19	214.13	54.00	234.12	156.69	404.23	153.23	100.70	160.07	170.64	534.17	223.88	117.01
Ni (mg/kg)	16.22	2.95	6.98	6.71	2.22	9.25	0.43	2.89	4.79	0.74	9.64	0.17	1.13	3.08	0.40	6.60	0.12	1.23	1.40	1.36	10.43	0.70	1.49	3.79	4.04
Se (mg/kg)	3.23	2.05	1.43	3.40	2.07	3.13	4.78	1.04	3.25	0.89	2.56	2.48	0.69	1.52	0.99	1.55	5.27	1.85	1.31	1.98	1.21	7.12	0.69	1.04	1.10
Sr (mg/kg)	17.43	1.32	0.33	0.17	0.59	9.76	0.56	0.21	0.27	0.71	14.90	1.42	0.53	0.86	1.30	5.79	0.89	0.38	0.64	0.35	10.23	0.63	0.39	1.03	0.39
V (mg/kg)	39.44	3.24	12.34	12.86	9.71	35.32	1.10	7.60	8.70	4.37	33.13	0.45	4.53	13.97	2.20	12.10	0.20	2.31	1.83	3.54	42.66	1.55	13.67	16.57	3.24
Zn (mg/kg)	59.88	30.22	40.00	30.33	13.38	25.03	6.72	30.59	50.13	14.00	20.01	1.17	7.68	45.62	24.41	23.99	4.34	26.50	42.12	9.68	21.33	9.53	31.85	72.70	3.89
Dy (mg/kg)	0.00	0.45	0.03	0.70	0.14	0.00	0.00	0.00	0.00	0.00	1.42	0.50	0.59	0.23	0.24	0.06	0.76	0.00	0.11	0.36	0.00	0.00	0.00	0.00	0.00
Tb (mg/kg)	0.59	0.37	0.23	0.44	0.37	0.52	0.36	0.24	0.33	0.49	1.30	0.63	0.28	0.37	0.25	0.43	0.32	0.20	0.36	0.47	0.29	0.13	0.13	0.30	0.33
Th (mg/kg)	0.00	10.32	4.70	5.06	187.53	0.05	10.93	5.54	0.43	189.68	0.47	40.28	37.38	2.27	546.38	1.91	179.62	97.23	9.25	1147.89	0.00	9.97	8.61	0.14	232.82
U (mg/kg)	0.00	18.03	12.42	8.41	1.86	0.00	7.11	2.40	5.48	8.00	0.02	13.70	8.88	7.90	62.60	0.02	30.36	14.18	14.32	66.17	0.00	10.29	5.42	3.76	18.86

Appendix A.4: China's National Standards for Water Pollution Control in Ion-Adsorption Rare Earth In-Situ Leaching

《离子型稀土矿原地浸矿水污染控制标准》

（审定稿）

编制说明

标准编制组

二〇二四年四月

目　录

1 工作简况

1.1 项目背景和标准编制的意义

1.1.1 项目背景

我国是世界上稀土资源最丰富的国家，储量和产量均占世界第一位。其中离子吸附型稀土是我国宝贵的、稀缺的、有限而不可再生的战略资源，重稀土元素含量高，是高新技术领域的重要支撑材料。

离子型稀土矿目前均采用原地浸矿开采工艺开采，由于矿体底板和水文地质条件的限制，向自然山体中注入浸矿剂所得到的稀土浸出液无法通过收液系统全部回收，存在少量稀土浸出液下渗进入地下水，影响地下水环境；并通过地下水和地表水的水力联系，影响地表水环境。在未采取有效污染控制措施的情况下，开采活动很容易造成区域性地下水污染和流域性地表水污染。水环境受到污染后，修复时间长、难度大、成本高。原地浸矿带来的水环境污染问题成为了制约离子型稀土行业发展的最大瓶颈。

现阶段国内稀土行业污染物排放标准主要有《稀土工业污染物排放标准》GB 26451-2011 和《离子型稀土矿山开采水污染物排放标准》DB36 1016-2018。GB 26451 的适用范围不包括采用溶液浸矿方式直接从稀土矿床浸出或堆浸获得离子型稀土浸取液的过程；DB36 1016 为江西省地方标准，给出了离子型稀土矿山开采企业水污染物排放限值，但没有针对离子型稀土矿山开采导致的废水无组织排放提出水污染控制措施。为了解决上述问题，现制定离子型稀土矿原地浸矿水污染控制标准，指导开采企业构建水污染防控体系，改善区域水环境质量，并为环境管理提供更科学依据。

由中国恩菲工程技术有限公司为课题承担单位、中国南方稀土集团参与的“离子型稀土矿区生态修复与治理技术及环境影响分析”课题（2021YFC2902204）是国家重点研发计划项目“离子型吸附型稀土矿绿色高效开发关键技术与装备”重要组成部分，离子型稀土矿水污染控制标准研究是该课题的主要研究内容之一。

因此，标准编制组对我国离子型稀土矿区水污染物排放规律、特征以及水污染控制措施进行研究，根据离子型稀土矿原地浸矿工艺特点、结合离子型稀土矿区的水文地质条件，统筹考虑行业主流生产工艺特征污染因子，开展《离子型稀土矿原地浸矿水污染控制标准》编制工作，科学管控开采活动，保护稀土矿区的

水体环境，促进行业健康发展。

1.1.2 标准编制的意义

（1）满足国家及生态环境主管部门的相关需求

我国尚无行业普遍适用的离子型稀土矿开采水污染控制相关的标准和规范，国外在离子型稀土矿开采方向关注较少，也无相关的标准和规范。通过本标准的制定，可使离子型稀土矿山开采的水污染控制有据可依。同时污染控制标准作为环境技术支撑体系的重要内容之一，可以作为环境影响评价、环境保护设施设计、竣工环保验收、排污许可证核发及其投产后的水污染控制管理等环境管理工作的依据。

（2）改善区域水环境质量

原地浸矿工艺对水体环境的影响主要来源于浸矿剂的渗漏，这种影响主要由水文地质条件决定，也与开采企业水污染控制有关。目前，国内部分稀土矿区在历史开采活动中依赖经验，未采取有效的污染控制措施，给矿区及周边水环境造成污染。原地浸矿带来的水环境污染问题成为了制约离子型稀土行业发展的最大瓶颈。本标准提出了离子型稀土矿山开采水污染控制要求、水污染控制措施和水污染物监测要求，通过尽可能减少水污染物排放，改善区域水环境质量。

（3）指导企业系统构建水污染防控体系

本标准提出了离子型稀土矿原地浸矿水污染控制应遵循的原则，指导开采企业根据原地浸矿工艺特点和矿区环境水文地质条件，系统构建水污染防控体系，并提出了水污染控制要求和控制措施，引导行业水污染控制技术进步，推动行业绿色发展。

1.2 任务来源

中色协科字[2022]17 号文《关于下达 2022 年第二批协会标准制修订计划的通知》，正式下达了协会标准《离子型稀土矿原地浸矿水污染控制标准》的制定计划，计划号为 2022-032-T/CNIA ，完成年限为 2024 年。

1.3 编制单位简况

1.3.1 中国恩菲工程技术有限公司

主编单位中国恩菲工程技术有限公司（以下简称中国恩菲）前身是中国有色工程设计研究总院（原北京有色冶金设计研究总院），成立于 1953 年，现为世

界五百强企业中国五矿、中冶集团骨干子企业，是一个以提供工程技术服务为核心业务的科技型企业。

中国恩菲在南方离子型稀土矿开采环境影响评价、污染防控方面做了大量工作，完成了我国第一个离子型稀土矿山无铵开采环境影响评价，率先开展了浸矿活动对生态环境影响的模拟试验，在赣南、粤北、湘南等多个离子型稀土矿区开展了环境影响分析和评价工作，作为离子型稀土矿山第一个环保管家，对离子型稀土矿水污染防控进行了多元化的探索和研究，在离子型稀土矿山环境保护方面具有丰富的经验。

中国恩菲牵头编制了《稀土工业污染物排放标准》GB 26451-2011、《有色金属冶炼业绿色工厂评价导则》YS/T 1403-2020 等标准，作为主要编制单位参与了《有色金属工业环境保护工程设计规范》GB 50988-2014、《稀土行业排污许可证申请与核发技术规范》HJ1125-2020、《环境影响评价技术导则 稀土矿采选》等标准的编制工作。参与了多项生态环境部等有关稀土行业环境保护的课题研究工作，先后参与了《典型地区稀土矿开发与生产环境风险评估与监督技术研究》环保公益性项目和《典型有色金属工业行业（铜、铅、锌、稀土等）排放标准中污染物项目筛选及排放限值研究》等与环境保护科研课题。

1.3.2 有研稀土新材料股份有限公司

有研稀土新材料股份有限公司（简称有研稀土）是 2001 年由北京有色金属研究总院作为主发起人对“稀土材料国家工程研究中心”进行整体改制而设立的股份公司。

有研稀土开发了一系列创新性成果，在行业内得到广泛应用，为稀土行业绿色可持续发展提供技术支撑。研发成功离子型稀土原矿绿色高效浸萃一体化新技术、低碳低盐无氨氮分离提纯稀土新工艺。已在 3 家企业规模化应用，解决困扰行业 30 多年的含放射性废渣污染难题，镁盐废水及 CO2 循环利用率＞90%；工序缩短 5 道；稀土总收率提高 8%以上，环境和经济效益显著。该成果涉及的两项核心技术分别于 2016 年和 2017 年获得中国有色金属工业协会科学技术一等奖，核心专利获得中国专利优秀奖。被列为稀土行业“十二五”十大突破技术之一，先后入选国家发改委、工信部、科技部、环保部的低碳技术目录、清洁生产技术推广方案等，成为我国稀土工业领域内具有代表性的清洁生产工艺。

有研稀土新材料股份有限公司作为主要单位制定了《稀土工业污染物排放标

准》、《稀土工业污染防治技术政策》等多项行业标准及技术规范。

1.3.3 中国稀土集团有限公司

中国稀土集团有限公司于2021年12月23日在江西省赣州市挂牌成立。中国稀土是在中国铝业集团有限公司、中国五矿集团有限公司、赣州稀土集团有限公司所属稀土资产重组整合的基础上，引入中国钢研科技有限公司、有研科技集团有限公司，按照市场化原则组建的以中重稀土为主的大型稀土集团，中国稀土旗下有中国稀有稀土股份有限公司、五矿稀土集团有限公司、中国南方稀土集团有限公司等三家骨干企业，业务范围涵盖稀土科技研发、勘探开发、冶炼分离、精深加工、下游应用、成套装备、技术咨询服务、进出口及贸易等领域，具备稀土全产业链发展能力。

1.3.4 生态环境部环境工程评估中心

生态环境部环境工程评估中心负责组织对规划、重大开发和建设项目环境影响评价文件的技术审核；开展重大经济政策与规划的环境影响调查研究，以及环境影响评价技术政策研究；承担政策、规划、战略环境影响评价，区域生态环境评价及“三线一单”的制度设计、相关政策与技术规范制修订，以及生态环境准入清单拟订技术支持工作；组织拟订环境影响评价方法与技术导则，开展环境影响评价领域信息及环境影响预测模式的研究；承担排污许可制管理、生态环境保护督察执法相关研究和技术支持工作；开展污染防治相关管理政策和技术研究。近年来，承担了国家及省部级项目100余项，获省部级科技奖励20余项，主持完成了50余项国家和省部级标准的制修订研究。在稀土行业污染源头防控方面开展了深入研究，牵头承担了国家重点研发计划“浸矿场地残留浸矿剂高效淋洗材料、技术与装备”项目（2018YFC1801800），主持《环境影响评价技术导则 稀土采矿选矿》《离子型稀土矿地下水污染风险防控技术指南》等标准规范制订研究，为稀土行业生态环境保护提供规范依据和技术支撑。

1.3.5 赣州稀土矿业有限公司

赣州稀土矿业有限公司是中国稀土集团的二级直管企业，是按照“19411”专业化整合方案组建的集团公司资源类区域化公司，统一管理江西区域稀土矿产资源开发和冶炼分离产业。公司拥有45本离子型稀土采矿权证，资源储量排在全国前列，是江西省稀土资源唯一采矿权人，聚焦稀土资源的勘探开发、分离冶炼、精深加工、科技研发、技术咨询服务等业务。在稀土资源县下设定南、龙南

等 7 家分公司负责矿山开采业务管理；直管赣州稀土龙南冶炼分离有限公司、赣州稀土（龙南）有色金属有限公司。公司拥有多项专利和专有技术。近年来，牵头承担了“固废专项”、参与“土壤专项”和“离子型稀土网络协同制造”等国家重点研发计划项目。

1.3.6　中稀（湖南）稀土开发有限公司

中稀（湖南）稀土开发有限公司（以下简称“中稀湖南”）是中国稀土集团有限公司的省级区域公司，负责湖南省区域内离子型稀土资源的统一开发、冶炼分离企业的统一管理和稀土产业发展工作。

中稀湖南拥有湖南省内唯一的一张稀土采矿权证即江华县稀土矿，已建成比较完整的稀土采选、灼烧、冶炼分离全产业链体系。旗下建有稀土精矿产能 2000 吨/年的江华县稀土矿，是目前国内离子型稀土矿山中装备最先进、自动化智能化程度最高的离子型稀土矿山，还配套建成了产能 5000 吨/年的绿色高效稀土冶炼分离厂。

1.3.7　龙岩市稀土开发有限公司

龙岩市稀土开发有限公司（以下简称“龙岩稀土”）成立于 2009 年 9 月 9 日，注册资本 5000 万元人民币。公司主要业务涵盖稀土原矿开采、稀土贸易、稀土原矿开采技术研发和服务等，是福建省内唯一的稀土矿山开采公司。自成立以来，公司积极参与探索“以发展精深加工为导向，多县产矿、集中分离，利益共享”的稀土资源管理机制，被中共中央办公厅肯定为稀土资源管理的“福建模式”。

龙岩稀土持续稀土矿山生产技术创新，联合黄小卫院士团队、中国科学院、中国地质科学院、江西理工大学、福建师范大学和南昌大学共同开发了离子型稀土资源绿色高效开采关键技术，并初步升级为离子型稀土资源高效绿色提取的数字驱动一体化技术，该项技术可达国际领先水平。目前，公司已获得多项省部级科学技术奖，为福建省内稀土产业的发展奠定了坚实的基础。

1.4　主要工作过程

标准计划下达后，主编单位按照全国有色金属标准化委员会和全国稀土标准化技术委员会的要求成立了《离子型稀土矿原地浸矿水污染控制标准》编制组。编制组成员有着丰富的离子型稀土矿山开采、设计和与其相关的环境影响技术评估及审核、环境保护设计和环境影响评价等工作经验。

2023 年 1 月，编制组编制了《离子型稀土矿原地浸矿水污染控制标准》大纲，进行了相关标准的调研与分析。

2023 年 1 月-7 月，编制组针对我国典型离子型稀土矿山进行了现场调研，对其环境影响和污染防治措施进行了分析研究，开展水污染控制要求和水污染控制措施等研究工作。根据调研和研究成果，结合多年的实践经验，完成标准及编制说明的编制工作。

2023 年 7 月 27 日，全国稀土标准技术委员会在内蒙古包头市召开了 2023 年度第五次稀土标准工作会议，会议对《离子型稀土矿山水污染控制标准（讨论稿）》进行了专家审议，与会专家提出了非常宝贵的意见和建议。

2023 年 8 月-9 月，编制组先后征求了有研稀土新材料股份有限公司、核工业北京化工冶金研究院、江西省钨与稀土产品质里监督检验中心、龙岩市稀土开发有限公司、雄安稀土功能材料创新中心有限公司、中国稀土集团有限公司、中稀(广西)金源稀土新材料有限公司、中稀(湖南)稀土开发有限公司、中稀(凉山)稀土有限公司、中稀广西稀土有限公司、定南大华新材料资源有限公司、广晟有色金属股份有限公司、赣州稀土矿业有限公司等公司的意见建议。编制组根据专家意见及相关单位意见对标准进行了修改完善，形成《离子型稀土矿山水污染控制标准（预审稿）》。

2023 年 9 月 21 日全国稀土标准技术委员会在四川省成都市召开了 2023 年度第六次稀土标准工作会议，会议对《离子型稀土矿山水污染控制标准（预审稿）》进行了专家审议，会后编制组根据专家意见对标准再次进行了修改完善，形成了《离子型稀土矿山水污染控制标准（审定稿）》。

2 行业概况

2.1 行业发展概况

2.1.1 我国稀土行业发展情况

中国是世界第一大稀土资源国，中国稀土资源不但储量丰富，而且还具有矿种和稀土元素齐全、稀土品位及矿点分布合理等优势。根据美国地质调查局(USGS)《矿产品概要 2020》报告数据，截止 2019 年末，世界稀土资源储量约 1.2 亿吨，其中中国稀土资源储量 4400 万吨（REO），约占世界稀土资源储量的 37%。2020 年全球稀土矿产量达到 24 万吨（REO），我国稀土矿产量为 14 万吨，占

全球产量的 58.3%，居全球第一位。

目前，我国多数稀土企业分布在大型稀土矿山所在地区，以区域稀土资源为中心，中国稀土产业形成了三大基地和南北两大稀土生产体系格局。三大基地分别位于内蒙古包头、四川冕宁和江西赣州为代表的南方七省，其中包头和冕宁地区以轻稀土为主，江西等南方七省以中重稀土为主。

我国稀土矿有三种矿型，一是混合型稀土矿，主要集中在内蒙古自治区，采用露天开采；二是氟碳铈矿，主要集中在四川省和山东省，采用露天和井下开采：三是离子型稀土矿，主要集中在江西省、福建省、湖南省、广东省、广西壮族自治区、云南省，采用原地浸矿方式开采。为了规范稀土行业管理，保障稀土资源的合理开发利用，促进稀土行业持续健康发展，保护生态环境和资源安全，稀土按照工信部年度计划指标开采。从 2016 年到 2021 年，三种矿型的开采量均呈上升趋势。

我国稀土企业从上世纪 80 年代的 300 多家，通过多年的市场整合及环保管理，2011 年我国稀土企业有 136 家。为贯彻落实《国务院关于促进稀土行业持续健康发展的若干意见》（国发（2011）12 号）和《国务院关于加强环境保护重点工作的意见》（国发（2011）35 号)，推动稀土行业持续健康发展，原环境保护部组织开展了稀土企业环保核查工作（《关于开展稀土企业环保核查工作的通知》，环办函（2011) 362 号），在 2011 年 11 月 22 日~2013 年 12 月 26 日相继公布了 4 批共 87 家符合环保要求的稀土企业名单。2013 年 1 月工业和信息化部发布《关于加快推进重点行业企业兼并重组的指导意见》，通过联合、兼并、重组等方式，大力推进资源整合，大幅度减少稀土开采和冶炼分离企业数量，提高产业集中度，基本形成以大型企业为主导的行业格局。稀土集团战略经调整，确定组建六大稀土集团，即：中国五矿集团公司、中国铝业集团公司、中国北方稀土集团、厦门钨业稀土集团、中国南方稀土集团和广东省稀土产业集团，上述 87 家企业大部分纳入六大集团。为进一步提高我国稀土产业集中度，提升稀土资源利用率和掌控力，2021 年 12 月，中国铝业集团有限公司、中国五矿集团有限公司、赣州稀土集团有限公司所属稀土资产重组整合的基础上，引入中国钢研科技有限公司、有研科技集团有限公司，按照市场化原则组建以中重稀土为主的大型稀土集团——中国稀土集团。

2.1.2 离子型稀土矿山开发

离子型稀土矿富含稀缺的中重稀土，而中重稀土是新一代电子信息、现代国防军工等高精尖领域不可或缺的关键原材料。我国离子型中重稀土资源储量占全球 80%以上，最早被发现并实现大规模开发利用。全球 90%以上的中重稀土产品由我国利用离子型稀土矿生产。因此，离子型稀土矿的战略地位极高。

我国离子型稀土矿资源主要集中在江西省、福建省、湖南省、广东省、广西壮族自治区、云南省，采用原地浸矿方式开采。江西稀土资源主要在赣州，主要集中在龙南、定南、寻乌、信丰、安远、赣县、全南、宁都 8 个县；目前，龙南和定南的稀土矿山在产。广东省内有 3 本稀土采矿证，包括 2022 年已取得采矿证的全国储量最大的离子型稀土矿山新丰稀土矿，目前在产的是平远县仁居稀土矿和大埔县五丰稀土矿。湖南省目前在开采的离子型稀土矿山为江华县稀土矿。广西离子型稀土主要分布在贺州、梧州、玉林和崇左等地，目前在开采的矿山为六汤稀土矿和钟山花山稀土矿。福建在产的离子型稀土矿山为龙岩稀土矿。

2.2 离子型稀土矿主要生产工艺及产排污情况

离子型稀土矿是原生稀土矿物经过长期风化、游离出来的稀土通过离子交换机制以离子吸附状态在黏土矿物上迁移富集而形成的稀土矿床。原地浸矿工艺是目前国家唯一允许的离子型稀土矿开采工艺。国内目前离子型稀土矿生产均采用原地浸矿工艺。现有离子型稀土矿原地浸矿开采工艺技术路线主要包括：硫酸铵浸矿-碳酸氢氨沉淀、硫酸镁浸矿-碳酸氢钠沉淀、硫酸镁浸矿-氧化镁富集、低浓度稀土离心萃取连续高效富集工艺。

2.2.1 主要生产工艺

原地浸矿工艺包括原地浸矿注液、收液和稀土富集。工艺流程见图 2-1。

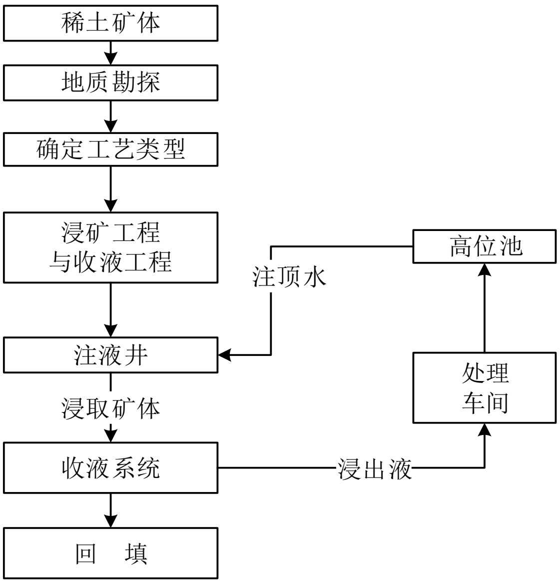

图 2-1　原地浸矿工艺流程

（1）注液

利用车间配液池配置浸矿剂溶液，配置高、中、低不同浓度浸矿剂溶液，分别在工艺池体进行存储；再根据稀土矿体分布设计建设注液井工程，浸矿剂溶液输送到高位池，再通过管线输送至浸采矿块注液井注入至矿体层；浸矿剂中阳离子与矿物表面的稀土发生离子交换，稀土离子扩散进入溶液生成稀土浸出液，完成注液过程。江华稀土矿山取消了高位池，浸矿剂溶液通过智能化泵送设备和管线系统，输送至浸采矿块注液井注入至矿体层。

目前生产使用的浸矿剂主要为硫酸铵和硫酸镁。

（2）收液

稀土浸出液一部分通过收液巷道，经巷道口沉砂池后导入集液沟；另一部分利用导流孔自然浸出进入集液沟，最终汇集后导排进入浸出液中转池；渗漏进入地下的部分浸出液经环保回收井截留后泵取至浸出液中转池；最后统一回收至车间浸出液池，完成收液过程。浸采矿块主要有以下两种类型：

① 裸脚式风化壳原地浸采矿块

裸脚式风化壳面型主要特点为侵蚀基准线出露位置较高，含水层隔水底板深度较浅，其标高高于侵蚀基准面，稀土浸出液可以顺着隔水底板以泉或散流形式在坡脚处自然流出，因而对于裸脚式风化壳采矿工艺为注液孔浸矿后，使用“导流孔+收液沟为主、环保回收井/沟为辅”的裸脚式原地浸矿工艺。

② 全覆式风化壳原地浸采矿块

全覆式风化壳面型主要特点为侵蚀基准线出露位置较低，含水层隔水底板深度相对裸脚式来说较深，因而不能形成天然底板，需要采用人工施工形成人工底板。因而对于全覆式风化壳原地浸采矿块的采矿工艺为注液孔浸矿后，使用“密集导流孔+人工底板收液巷道为主，收液沟+环保回收井/沟为辅”的全覆式原地浸矿工艺。

（3）稀土富集

①沉淀富集工艺

离子型稀土矿常规的稀土富集工艺为碳酸氢铵沉淀富集工艺。原地浸矿收液得到的浸出液（浸出液）在车间进行处理，用碳酸氢铵进行除杂、沉淀富集得到碳酸稀土产品。部分企业实现自动化控制，其稀土富集工段的工艺流程为：回收至车间的稀土浸出液，经 6 级串联搅拌槽除杂后，进入除杂浓密池进行固液分离得到含稀土除杂浸出液；除杂浸出液自除杂浓密机自流到 6 级串联搅拌槽进行产品沉淀，沉淀后的产品浆液进入浓密机进行固液分离得到产品和清液；最后压滤得到稀土碳酸盐产品，清液回用于配置浸矿剂。

工艺流程见图 2-2。

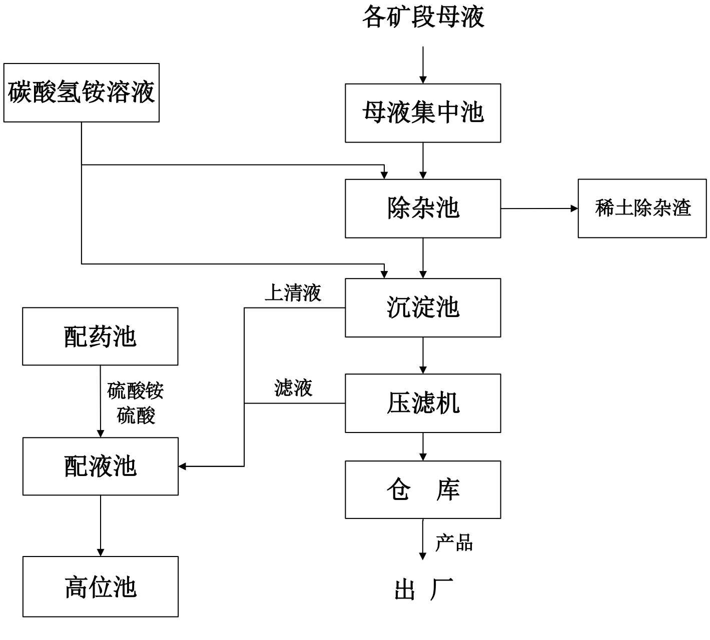

图 2-2 碳酸氢铵沉淀富集工艺流程

部分离子型稀土矿山企业目前采用硫酸镁为浸矿剂，氧化镁进行沉淀富集。

其稀土富集工段的工艺流程为：浸出液经收液系统输送至富集池。在富集池中，加入氧化镁浆液，池中溶液经澄清后，富集后的沉淀物为产品氢氧化稀土及少量杂质。

部分离子型稀土矿山企业在进行碳酸氢钠沉淀富集工艺相关实验。

②低浓度稀土离心萃取连续高效富集工艺

有研稀土和有研集团创新开发出低浓度稀土离心萃取连续高效富集工艺，主要工艺由浸出液预处理、非平衡离心萃取、反萃、有机相回收和浸矿剂制备等工序组成，从稀土矿浸出浸出液中生产出氯化稀土产品，萃取的有机相循环利用、萃余液回用于浸矿剂的制备。工艺流程较沉淀法缩短 5 道工序，稀土收率提高 8 个百分点。

2.2.2 产污环节

相比已淘汰的堆浸、池浸工艺，原地浸矿工艺最大程度上保护了矿区的生态环境，但是也存在一定的局限性，主要体现在浸矿剂的渗漏对水环境的影响。原地浸矿过程中无法保证全部回收稀土浸出液，不可避免会有极少部分稀土浸出液渗漏。矿区水污染源主要为浸矿剂的渗漏，即渗漏尾水，主要以以下几种方式体现：①浸矿剂渗漏到地下水中，离子稀土矿区地下水和地表水联系紧密，渗漏的地下水在某些区域出露于地表；②正在开采的矿块，赋存在土壤中的污染物在丰水期雨水淋溶时，在矿区会形成汇流，淋溶水中含有污染物；③已开采的矿块即使经过清水淋洗，在丰水期雨水淋溶仍会产生含污染物的淋溶水。

2.2.3 污染防治措施

（1）氨氮废水的处理措施

硫酸铵浸矿-碳酸氢铵沉淀工艺产生的废水主要是含氨氮尾水，氨氮尾水的收集、处理是采用该工艺矿山污染防治的重点。

离子型稀土矿氨氮尾水中污染因子相对单一、污染物浓度存在一定的波动、碳氮比低、可生化性差，其氨氮浓度与矿山的开采强度和水文地质特征关系密切。目前离子型稀土矿山氨氮废水处理工艺有化学沉淀法、化学氧化法、生物法、膜处理法、吹脱法及其组合等工艺。

化学沉淀法，在一定的 pH 值条件下，通过往废水中投加镁盐和磷酸盐，水中的 HPO_4^{2-}、NH_4^+和 Mg^{2+}可以生成磷酸铵镁沉淀，使铵离子从氨氮废水中分离出来。

化学氧化法，在含氨氮的水中加入次氯酸钠或氯气，次氯酸根离子能够与水中的氨氮反应产生一氯胺（NH_2Cl）、二氯胺（$NHCl_2$）和三氯胺（NCl_3）。

生物法，一般包括硝化和反硝化两个阶段，是利用硝化菌和反硝化菌完成的。其中硝化作用包括亚硝化与硝化两个阶段：亚硝化过程是由亚硝酸菌将氨态氮转化为亚硝酸盐，硝化过程是由硝酸菌将亚硝酸盐进一步氧化为硝酸；反硝化主要作用是将硝酸盐或亚硝酸盐还原成气态氮（NO、N_2O、N_2），是在厌氧或缺氧的条件下完成。反硝化阶段需要投加碳源。

膜处理法是利用特定膜的透过性能对溶液中的某种成分进行选择性分离，可在室温、无相变的条件下进行，主要包括电渗析、反渗透、超滤及渗析等工艺。膜处理法投资较高，但出水水质好，还对氨进行回收。

吹脱法，主要要基于气液传质的原理，通过调节氨氮废水的 pH 使 NH^{4+}转化为气态 NH_3，然后通过曝气使水中 NH_3 向大气中转移，以达到去除氨氮的目的。

（2）其他废水处理

使用硫酸镁作为浸矿剂的离子型稀土矿山生产企业，需要对废水中的硫酸盐和镁进行处理，以满足污染控制标准的要求。目前采用的有钙矾石法，添加适量氧化钙、偏铝酸钠和絮凝剂等试剂去除水中的硫酸盐和镁。

3 编制原则

本标准编制的主要原则是：

（1）科学性。以国家环境保护相关法律、法规、规章、政策和规划为指导，以改善生态环境质量为目标，结合离子型矿山开采工艺特点，制定水污染控制标准。

（2）可行性。标准制定过程中，充分调研离子型稀土矿山生产企业水污染控制技术，广泛收集意见和建议，使标准具有可实施性，促进环境质量改善。

（3）系统性。离子型稀土矿原地浸矿水污染控制应遵循“源头削减控制、过程监管预警、末端风险防控”的原则，促进清洁生产，过程控制，防控风险。

4 主要技术内容及确定依据

4.1 主要技术内容的确定

4.1.1 标准的适用范围

根据《产业结构调整指导目录（2024 年本)》，“离子型稀土矿堆浸和池浸工艺”被列为淘汰类项目。因此，本标准适用于采用原地浸矿工艺的离子型稀土

矿开采企业水污染控制管理，以及新建、改建和扩建离子型稀土矿山开采建设项目的环境影响评价、环境保护设施设计、竣工环保验收、排污许可证核发及其投产后的水污染控制管理等。

4.1.2 标准的框架架构

《离子型稀土矿原地浸矿水污染控制标准》包括如下章节：

前言

1 适用范围

2 规范性引用文件

3 术语和定义

4 水污染物控制要求

5 水污染物控制措施

6 水污染物监测要求

4.1.3 术语和定义

为便于理解和应用本标准，在第 3 章中定义了 15 个术语。“稀土”、“离子型稀土矿”、“稀土浸出液”等离子型稀土矿常用 3 项术语，来源于《稀土术语》（GB/T 15676-2015）的基础上结合本标准特点修改后给出；“对照断面”来源于《地表水监测技术规范》（HJ 91.2—2022）的基础上结合本标准特点修改后给出；“地下水环境监测井”来源于《地下水环境监测技术规范》（HJ 164-2020）的基础上结合本标准特点修改后给出；结合离子型稀土矿采矿选矿过程中污染防控的需要及实践，编制组给出了包括“原地浸矿”、“污染监控断面”、“管控断面”、“环境质量达标断面”、“地下水环境控制范围”、“对照监测井”、“污染扩散监测井”、“环境影响跟踪监测井”、“环保回收井”、“地下水抽提系统”、共 10 项术语和定义。

4.2 水污染控制要求中污染物项目和浓度限值的确定

4.2.1 污染物控制项目的确定

在对离子型稀土矿区产污情况进行分析，以及对废水污染特性测定的基础上筛选确定特征污染控制指标。特征污染因子的筛选综合考虑了以下几个因素：（1）产生量大；（2）对人体、环境生物毒性强或对生态环境危害大；（3）能有效控制；（4）具备有效的检测与监测方法。

2018 年前审批的环评及竣工环保验收中，离子型稀土矿采矿项目水污染物

控制参照《稀土工业污染物排放标准》GB 26451-2011 标准执行。而 GB 26451-2011 中明确该标准不包括采用溶液浸矿方式直接从稀土矿床浸出或堆浸获得离子型稀土浸取液的过程。因此，离子型稀土矿原地浸矿开采目前无适用水污染物排放国家标准。

2018 年，江西省发布《离子型稀土矿山开采水污染物排放标准》DB36 1016-2018，江西省离子型稀土矿采矿项目执行该标准，控制项目和标准值基本与 GB 26451-2011 保持一致，增加了硫酸盐的特征污染指标。

标准编制组调研走访广西崇左、广西贺州、福建龙岩、江西赣州、广东平远和湖南江华等离子型稀土矿区，收集了各矿区采选工艺技术、产排污环节、污水处理设施、环境影响现状监测等技术资料，目前各矿区污水处理设施排放口水污染物限值均按 GB 26451-2011 或 DB36 1016-2018 执行，管控断面多执行《地表水环境质量标准》GB 3838-2002，也有个别矿区参照 DB36 1016-2018 执行。

收集的监测数据表明：总铬、六价铬在渗漏稀土浸出液以及离子型稀土矿区周边地表水、地下水中均未检出或浓度极低，因此编制组认为总铬、六价铬不属于离子型稀土矿原地开采工艺的特征污染因子，在本次标准中未对总铬、六价铬提出限值要求。因 GB 3838-2002 标准中无悬浮物项目，离子型稀土矿区位于山区，降雨时流经矿区的河流携带泥沙，造成悬浮物增加，并非矿山开采特征污染因子，因此本次标准中未对悬浮物提出限值要求。目前离子型稀土矿区浸矿剂普遍采用硫酸铵和硫酸镁，稀土浸出液及尾水中硫酸盐含量较高，硫酸盐为 GB 3838-2002 表 2 集中式生活饮用水地表水源地补充项目标准限值，因此本次标准中对硫酸盐提出限值要求。

污染物项目参照 GB 26451-2011 中的污染物项目确定。与 GB 26451-2011 相比，减少了悬浮物、总铬和六价铬 3 项指标，增加了硫酸盐 1 项指标。具体各控制项目选定依据如下：

pH：离子型稀土矿山开采使用硫酸氨或硫酸镁浸矿液 pH 值多为 4-5，浸出液及尾水中 pH 较低，不能直接排入外部水环境。pH 值决定了水体的酸碱状态，影响水体中化学物质的溶解度和生物体的生存环境。在酸性水中，有毒的重金属如铅、镉等容易溶解，对生物造成更大的危害，对水环境的影响非常显著。因此 pH 应确定为离子型稀土矿原地浸矿水污染控制标准的控制项目。

氟化物：受地质环境影响，部分离子型稀土矿区内广泛分布燕山期岩浆岩体，部分区域受含氟矿物溶解影响，氟化物本底值高，部分氟化物随开采活动被浸出液带入。氟化物是一种对人体必需的微量元素，但过量的氟会导致氟中毒，主要表现为牙齿和骨骼的损害。氟化物可以通过食物链累积和放大，对人类健康构成风险。氟化物对水生生物也有影响，高浓度的氟化物可能对水生生物造成毒性效应，影响生物多样性和生态系统的健康。因此氟化物应确定为离子型稀土矿原地浸矿水污染控制标准的控制项目。

CODcr、石油类、总磷：部分离子型稀土矿区采用绿色高效浸萃一体化工艺，使用有机物做为萃取剂，涉及特征污染因子 CODcr、石油类、总磷。CODcr 反映水体中受还原性物质污染的程度，CODcr 指标反映水体中还原性物质的污染情况，CODcr 指标易于监测、重点性强，总磷是水体中磷元素的总和，是水体富营养化的主要原因之一，对水质产生严重影响，总磷超标会导致水体富营养化、水体产生异味甚至出现水华。因此选取 CODcr、石油类、总磷作为控制指标。

氨氮、总氮：目前部分离子型稀土矿区采用硫酸铵浸矿，氨氮及总氮产生量大。氨氮是水体中的营养素，可以导致水富营养化现象产生，是水体中的主要耗氧污染物，对人体、鱼类和水生生物有危害，氨氮超标会引起水体富营养化，导致水体中的藻类大量繁殖，挤占鱼类和水生生物的氧气，影响鱼类和水生生物的健康，氨氮在一定条件下可转化为亚硝酸盐，长期饮用氨氮超标的水可能对人体健康产生严重影响，形成强致癌物质亚硝胺。总氮是水体中所有形态氮的总和，包括氨氮、亚硝酸盐氮、硝酸盐氮等，是水体富营养化的重要指标之一。总氮污染与氨氮类似，也是水体中的主要耗氧污染物，对水生态环境有负面影响。因此选取氨氮、总氮作为控制指标。

硫酸盐：目前离子型稀土矿区均采用硫酸盐作为浸矿剂，使用量大，硫酸根自由基（SO_4^{2-}）在水处理过程中因其强氧化性被用于降解有机污染物。然而，硫酸根自由基的氧化过程也可能与环境中的无机离子反应，生成有毒、有害副产物，如硝基芳香化合物，这些物质对生态系统和人类健康构成潜在风险。硫酸根自由基的氧化作用下，环境中的铵氮（NH^{4+}）可以转化为硝酸盐，过程中可能产生亚硝酸盐和二氧化氮自由基等中间体，这些物质可能进一步与有机质反应生成硝基酚等副产物，引起二次污染。因此选取硫酸盐作为控制指标。

总锌、总镉、总铅、总砷：离子型稀土矿山往往与铅、砷、镉、锌共生，根据收集的监测数据浸出液及尾水中均有总锌、总镉、总铅、总砷检出。高浓度的锌会对水生生物造成急性毒性，影响其生长、繁殖和生存。镉分类为人类致癌物，能在生物体内积累，导致肾脏损伤和骨骼疾病。铅是一种神经毒素，对儿童的神经系统发育影响尤其严重。水体中的铅可以通过食物链累积，影响人类和野生动物。砷是一种已知的人类致癌物，其化合物具有不同的毒性。砷可以在水生生物体内累积，并通过食物链影响人类健康。因此选取总锌、总镉、总铅、总砷作为控制指标。

钍铀总量：离子吸附型矿往往和含钍、铀的矿物共生但比例较低，放射核素钍铀随着稀土的富集而富集，它们在水体中的浓度增加会提高水体的放射性水平，对水生生物和通过食物链对人类健康构成潜在风险。铀的一些化合物，如六价铀，具有一定的化学毒性，可以影响水生生物的健康。《污水综合排放标准》GB 8978-1996 中采用水污染控制因子的是总α放射性和总β放射性，考虑到总α放射性和总β放射性的剂量主要与放射性物质针和铀的总量关系密切。总α放射性和总β放射性的测定相对较困难，将对地方环保监测部门的监测带来诸多限制，因此采用易于测定且成本相对更低的指标钍铀总量代替，并且与《稀土工业污染物排放标准》(GB26451-2011)的放射性监测指标一致，便于监管。因此选取钍铀作为控制指标。

最终确定本标准主要污染物控制因子包括 pH、氟化物、石油类、化学需氧量、总磷、总氮、氨氮、硫酸盐、总锌、总镉、总铅、总砷、钍铀总量共 13 项污染物项目。本标准水污染控制要求中分别对管控断面控制浓度限值、污染监控断面水污染物预警浓度限值及污水处理设施排放口水污染物限值提出了不同的要求。

管控断面污染控制因子包括 pH、氟化物、石油类、化学需氧量、总磷、氨氮、硫酸盐、总锌、总镉、总铅、总砷共 11 项。

污染监控断面水污染物预警浓度限值选取了离子型稀土矿山最具特征的污染控制因子为氨氮、硫酸盐等 2 个项目。

污水处理设施排放口污染物控制因子包括 pH、氟化物、石油类、化学需氧量、总磷、总氮、氨氮、硫酸盐、总锌、总镉、总铅、总砷、钍铀总量共 13 项。

4.2.2 限值的确定

4.2.2.1 管控断面水污染物控制浓度限值

本标准中的管控断面水污染物控制浓度限值中特征因子氨氮、氟化物（背景值高矿山）不高于《地表水环境质量标准》GB3838-2002 表 1 地表水环境质量标准基本项目标准限值Ⅲ类水质标准限值的 2 倍；硫酸盐不高于《地表水环境质量标准》GB3838-2002 表 2 集中式生活饮用水地表水源地补充项目标准限值的 2 倍；其余因子不高于《地表水环境质量标准》GB3838-2002 表 1 地表水环境质量标准基本项目标准限值Ⅲ类水质标准限值。具体限制确定的过程如下：

氟化物：因部分离子型稀土矿山位于高氟地区，受地质条件影响，即使未进行开采，也存在地表水氟化物超过 GB3838-2002 表 1 的Ⅲ类水质标准限值的情况。因此，本标准中对应氟化物浓度进行了两种情况的限定。当对照断面氟化物浓度＜1mg/L，管控断面应满足《地表水环境质量标准》GB3838-2002 表 1 地表水环境质量标准基本项目标准限值Ⅲ类水质标准限值。

氟化物广泛存在于天然水体中,是人体必须的微量元素之一，缺氟易患龋齿病，饮水中含氟的适宜浓度为 0.5~1.0mg/L。若饮用水中含氟量高于 4mg/L 时，可导致氟骨病。氟化物在水体中绝大部分以离子状态存在，极易被组织吸收，沉积在鱼体各组织器官。从而影响鱼类品质，甚至造成鱼病。地表水环境质量标准 GB3838-2002 和渔业水质标准 GB11607-89 中规定氟化物不得超过 1.0mg/L；饮用天然矿泉水标准 GB8537-1995 规定氟化物应小于 2.0mg/L。离子型稀土矿区均不得设置在饮用水源保护区上游，重点考虑氟化物对鱼类影响，相关研究表明鱼体肌肉中氟含量随着水体中氟化物含量的增加而增大。氟含量低于 4mg/L 水体的养殖鱼类(除雅罗鱼外)肌氟含量均较低，大多数未超出无公害食品标准。因此，对鱼类品质不会造成影响。综合考虑技术可达性，标准编制组认为当对照断面氟化物浓度≥1mg/L 时，因矿山开采导致的氟化物增量应在 1mg/L 内，即管控断面氟化物浓度应≤2mg/L。

氨氮：氨氮对水生生物毒性效应明显，是我国地表水环境质量标准（GB 3838—2002）的基本项目之一，也是我国水环境主要污染物排放总量控制的约束性指标之一。《淡水水生生物水质基准—氨氮》（2020 年版）（详见附件 1）是在我国氨氮水质基准前期研究的基础上，依据《淡水水生生物水质基准制定技术指南》（HJ 831-2017）制定，反映现阶段水环境中氨氮对 95%的中国淡水水生

生物及其生态功能不产生有害效应的最大浓度，可为制修订相关水生态环境质量标准、预防和控制氨氮对水生生物及生态系统的危害提供科学依据。收集的监测数据表明，离子型稀土矿山区域地表水 pH 值大多在 6.09~6.94 之间，水体温度维持在 10~20℃之间，对照附表氨氮长期水质基准在 1.5~2mg/L 之间。在氨氮≤2mg/L 的情况下，氨氮基本对地表水中淡水水生生物及其生态功能不产生有害效应，对环境影响较小，因此本标准管控断面氨氮浓度限值定为 2mg/L。

硫酸盐：硫酸盐的标准值因研究基础资料的缺乏，未有推导出基准推荐值。查阅相关论文，在低浓度下，硫酸盐对水生生物是必需的营养素，对藻类生长有积极影响，当硫酸盐浓度低于 0.5 mg/L 时，藻类生长会受到抑制。然而，在高浓度下，硫酸盐可能成为天然水中的主要污染物，对植物或动物并不具有毒性。在人体内，硫酸盐的浓度为 500-750 mg/L 时会引起暂时性的通便作用，但更高浓度并未引起长期的不良影响。在非常高的浓度下，硫酸盐对牛等动物可能有毒。人们常把硫酸镁含量超过 600mg/L 的水用作导泻剂。结合实测结果参考已有的国家标准，如《地表水环境质量标准》GB3838-2002、《污水综合排放标准》GB 8978-1996、《稀土工业污染物排放标准》GB 26451-2011 的标准值。在 GB8978-1996 和 GB 26451-2011 中均未对硫酸盐的排放限值浓度进行约束，GB3838-2002 表 2 集中式生活饮用水地表水源地补充项目标准限值为 250mg/L。本标准根据收集的监测数据，各离子型稀土矿区对照断面硫酸盐浓度基本在 100mg/L 以下。矿区采用硫酸盐浸矿，各矿区监测断面硫酸盐监测结果跨度较大，矿区内硫酸盐含量较高，在 259~1025mg/L 之间，矿区外硫酸盐监测数据在 84.3~249mg/L 之间。随着开采面积扩大硫酸盐累积效应明显，同时考虑硫酸盐的毒性情况，将管控断面硫酸盐限值定为 500mg/L。

污染物控制浓度限值，是以改善生态环境质量为目标、综合考虑经济技术成本确定的。本标准管控断面水污染物控制浓度限值与 GB3838 污染物项目浓度限值对比见**错误!未找到引用源。**。

表 4-1 本标准管控断面水污染物控制浓度限值与 GB3838 污染物项目浓度限值对比（单位：mg/L）

控制污染物	本标准	《地表水环境质量标准》GB3838-2002Ⅲ类水质标准
pH（无量纲）	6~9	6~9
氟化物（以 F 计）	1[a]（2[b]）	1
石油类	0.05	0.05

化学需氧量（CODcr）	20	20
总磷	0.2	0.2
氨氮	2	1
硫酸盐（以 SO_4^{2-}计）	500	250^c
总锌	1.0	1.0
总镉	0.005	0.005
总铅	0.05	0.05
总砷	0.05	0.05
注： [a] 适用于对照断面氟化物浓度＜1mg/L 的矿山； [b] 适用于对照断面氟化物浓度≥1mg/L 的矿山； [c] 硫酸盐浓度限值来源为《地表水环境质量标准》GB3838-2002 表 2 集中式生活饮用水地表水源地补充项目标准限值。		

4.2.2.2 污染监控断面水污染物预警浓度限值

因离子型稀土矿区原地浸矿工艺特点，为确保管控断面满足水污染控制要求，本标准要求矿山开采企业在矿区内设置若干污染监控断面（每个开采矿块下游 100m 地表水断面、下游 200m 地表水断面），并对应设置预警值，超过预警值应及时启动末端风险防控措施，并减少生产规模，确保管控断面满足水污染控制要求。

主要设定氨氮和硫酸盐作为水污染物预警因子。开采矿块下游 100 米地表水污染监控断面预警浓度值设定为氨氮 30mg/L、硫酸盐 800mg/L；开采矿块下游 200 米地表水污染监控断面预警浓度值设定为氨氮 10mg/L、硫酸盐 500mg/L。

因预警值为企业内部控制指标，在浓度限值控制上结合管控断面及排放口污染物浓度限值，同时参照生产企业实际经验进行设定。

4.2.2.3 污水处理设施排放口水污染物排放浓度限值

（1）确定原则

本标准中的污水处理设施排放口水污染物排放浓度限值不高于《稀土工业污染物排放标准》GB 26451-2011、《污水综合排放标准》GB8978-1996 以及《离子型稀土矿山开采水污染物排放标准》DB36 1016-2018 中的水污染物排放限值。污染物浓度限值，是以改善生态环境质量为目标、综合考虑经济技术成本确定的。所确定的污染物排放限值，应是国内外目前采用且成熟可靠的废水处理工艺在加强管理的基础上能达到的。

（2）制定依据

①pH（无量纲）、氟化物（以 F 计）、石油类、化学需氧量（CODcr）、总

磷、总氮、氨氮、总锌、总镉、总铅、总砷、钍铀总量的浓度限值参照《稀土工业污染物排放标准》GB 26451-2011 表 2 新建企业水污染物排放浓度限值确定。

②氨氮参照《稀土工业污染物排放标准》GB 26451-2011 表 3 水污染物特别排放限值确定

③硫酸盐（以 SO_4^{2-}计）：硫酸盐（以 SO_4^{2-}计）浓度限值参照《离子型稀土矿山开采水污染物排放标准》DB36 1016-2018“表 1 离子型稀土矿山开采企业水污染物排放浓度限值”中的一级排放标准，即 800mg/L。本标准与 GB 26451 污染物项目浓度限值对比见表 4-2。本标准与 GB 26451 污染物项目浓度限值对比见表 4-2。

表 4-2 本标准与 GB 26451 污染物项目浓度限值对比（单位：mg/L）

控制污染物	本标准	《稀土工业污染物排放标准》GB 26451-2011 表 2 新建企业水污染物排放浓度限值直接排放标准
pH（无量纲）	6~9	6~9
氟化物（以 F 计）	8	8
石油类	4	4
化学需氧量（CODcr）	70	70
总磷	1	1
总氮	30	30
氨氮	10	15
硫酸盐（以 SO_4^{2-}计）	800	/
总锌	1	1
总镉	0.05	0.05
总铅	0.2	0.2
总砷	0.1	0.1
钍、铀总量	0.1	0.1

4.2.3 达标分析

本标准所涉及的水污染物采用化学沉淀法、化学氧化法、生物法、膜处理法、等处理措施可有效去除。对离子型稀土生产企业污染治理状况的调研结果表明，采取本标准提出水污染控制措施，因地制宜的系统构建矿区水污染防控体系，离子型稀土矿山开采企业污水处理设施排放口的水质可满足排放要求。

根据目前收集的各离子型稀土矿山污水处理设施排放口的水质监测数据，氨氮浓度一般 1~10mg/L 之间，硫酸盐浓度一般在 20-700mg/L 之间，重金属总锌、总镉、总铅、总砷及放射性元素钍铀总量均能满足限值要求，其余因子也均能满足限值要求。

根据目前收集的各离子型稀土矿山地表水监测数据，对照断面氟化物浓度＜1mg/L 的矿山，管控断面氟化物浓度虽然有所增加，但仍能保持 1mg/L 以下，满足《地表水环境质量标准》GB3838-2002 表 1 地表水环境质量标准基本项目标准限值Ⅲ类水质标准限值。对照断面氟化物浓度＞1mg/L 的矿山，管控断面氟化物浓度有所增加，在 1.34-1.89mg/L 之间，能够满足本标准设定的标准要求。管控断面氨氮超标较为严重，硫酸盐、氟化物、铅、镉和石油类在部分断面超标。通过本标准的实施，促进绿色清洁生产工艺的推广及淘汰环境敏感地区生产工艺、污染治理技术落后的离子型稀土生产企业。

4.2.4 单位产品基准排水量的确定及制定依据

目前部分矿区废水处理设施主要处理历史遗留矿区产生的废水，属于流域治理措施，因此在本标准中明确单位基准排水量不适用于采取流域治理措施的污水处理设施排放口。

离子型稀土矿废水包含浸采矿块生产尾水、渗漏废水和浸采矿块残留浸矿剂淋溶废水。根据收集目前在产离子型稀土矿原地浸矿工艺项目水平衡表明，正常在无降雨的情况下，企业收液量小于注液量，废水经处理后全部回用不外排，还需要补充部分新水。在降雨情况下，虽设置了避水沟、排水沟等措施，仍有部分雨水进入生产系统，导致降雨期出现收液量大于注液量的情况，目前某矿区统计降雨期日收液量约比注液量高 1500-1800m^3/d，多出的水量须经生化法污水处理设施处理后达标排放，全年降雨 60 天计算，全年生产 2000tREO，折算约排放 45~54m^3/d，因此，本标准结合矿山生产实际，定为 60m^3/t-REO。

4.3 水污染物控制措施的确定

我国南方离子型稀土矿的赋存和开采方式与其他矿体有很大的差别，离子型稀土赋存分散，点多面广，厚度不大，品位较低。原地浸矿浸采矿块的施工、浸矿、收液时间较短，一般每个浸采矿块的生产周期大约 1 年。离子型稀土矿原地浸矿开采对环境的影响主要为地下水和地表水环境，主要原因是浸采矿块浸矿稀土浸出液和浸矿剂等受水文地质条件限制难以完全回收，通过矿层下部底板裂隙等优势通道渗漏进入下游地下水体，并随着地下水迁移，矿区地下水与地表水水力联系密切，因此，原地浸矿开采工艺对地下水和地表水环境存在一定的污染风

险。

离子型稀土矿水污染防控措施的最终目标是恢复矿区内地表水地下水的环境功能和使用功能，但受原地浸矿开采工艺特点等客观条件的限制，将风险管控作为阶段性目标是必要的，通过采取水污染风险管控措施，控制矿区内水污染扩散，阻断矿区外水污染暴露途径，防止对矿区一定范围外的水环境产生影响，这也符合目前《污染地块地下水修复和风险管控技术导则》（HJ 25.6-2019）中水污染防控的总体思路。

整体而言，离子型稀土矿原地浸矿开采涉及水环境范围大、影响远，单独的环保措施难以形成联防联控的作用。编制组通过广泛调研赣州稀土矿业有限公司龙南和定南稀土矿、中稀（湖南）稀土开发有限公司江华稀土矿、广晟有色金属股份有限公司平远华企稀土矿山等典型在产离子型稀土矿现有水污染防控措施，并结合国内主流咨询设计、水污染处理和矿山生态修复等各领域相关单位多年在离子型稀土矿开展的设计、环评和污染防治工程经验，系统构建了以“源头消减控制、过程管控预警、末端风险应急”为核心的水污染防控体系（图 4-1），并在多个矿山企业进行实践应用，取得了较好的水污染防控效果。

基于上述工作，本标准给出了离子型稀土矿原地浸矿水污染控制措施的基本要求，以及在源头削减控制、过程监管预警和末端风险防控等方面具体措施。

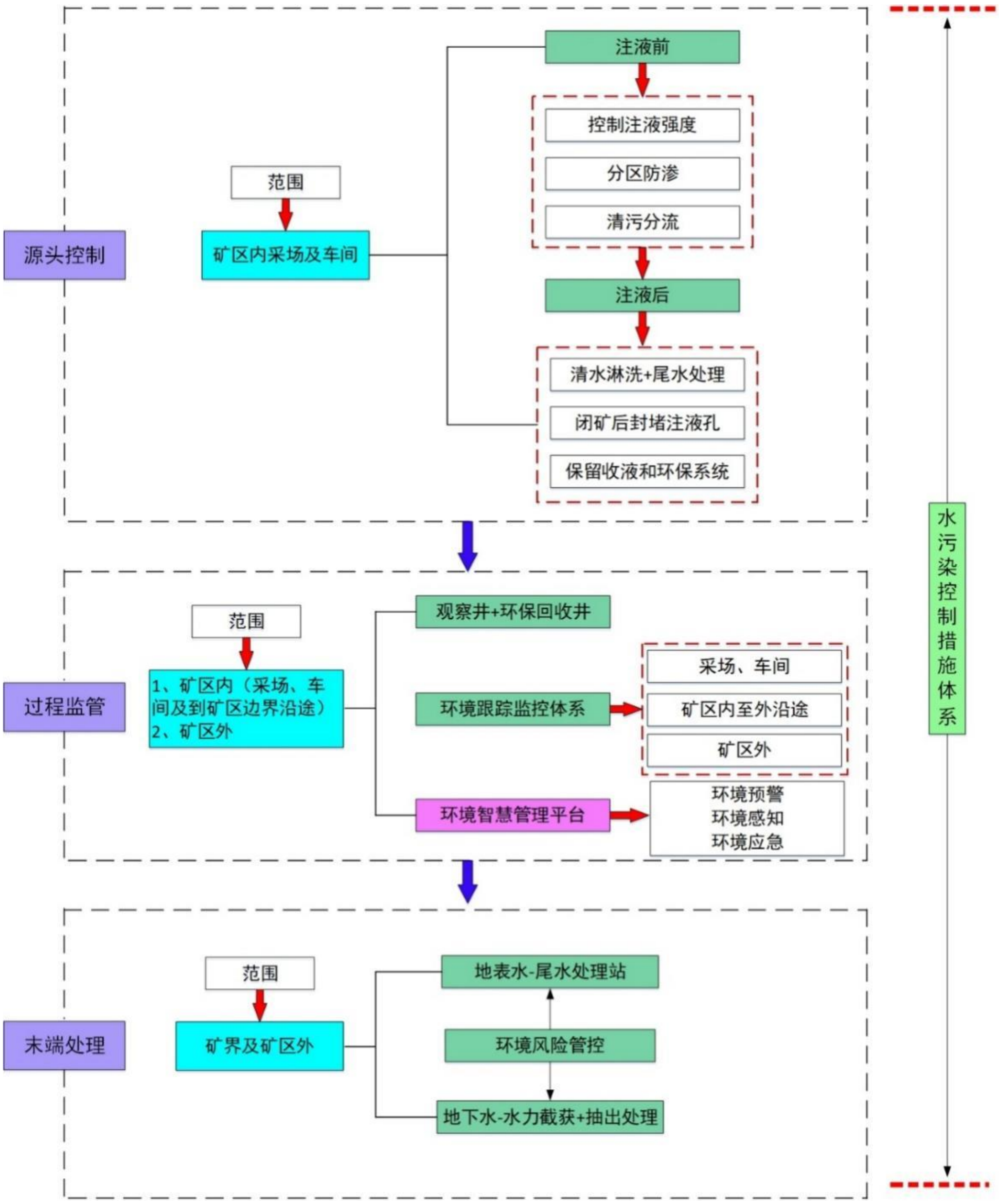

图 4-1　离子型稀土矿原地浸矿水污染控制措施体系

4.3.1　水污染控制措施基本要求

本标准根据现有技术水平和主流水污染防控原则方法，结合离子型稀土矿水污染控制的实践经验，给出了离子型稀土矿原地浸矿水污染控制应遵循的原则和路径，结合矿区实际环境水文地质条件，系统构建适用于各自矿区的水污染防控体系。同时，对原地浸矿开采区选址、规划浸采范围和顺序、控制浸采强度等方面给出了原则性的要求。并要求离子型稀土矿开采企业在开采过程中进行精细化环境管理和水污染防控，采取有效措施减少水污染渗漏扩散，提高水资源循环利用水平，确保水环境管控断面达到相应的排放控制限值和水环境质量达标断面满

足环境质量要求。

4.3.2 水污染源头削减控制措施

针对源头削减控制措施，本标准提出了浸采区清污分流和稀土车间雨污分流措施。即在浸采区收液系统的上方设置内部避水沟，将山体地表径流收集进入避水沟；在收液沟外部设置排水沟，将雨水和山泉水收集入排水沟；或将收液沟外侧壁设置高于地面 20-30cm，防止外侧雨水进入收液沟。上述措施均可以防止山体的清水径流汇入浸出液收集系统与稀土浸出液混合。对车间设置溢流导排设施，防止因工艺池体液体溢流造成水环境污染，根据车间整体的坡度和布局设置雨水导排设施，防止雨水进入工艺池体或者造成水土流失。

针对稀土浸出液和受污染水体渗漏污染地下水，本标准提出应进行地下水分区防渗。即根据场地水文地质条件和包气带防污性能，结合工程建设设计标准和《环境影响评价技术导则 地下水环境》HJ 610-2016 的分区防渗要求，可将整个场地分为重点防渗区、一般防渗区和简单防渗区。离子型稀土矿浸采矿块收液系统（集液巷道、收液沟、集液池等）一般为临时性工程，且为了利于收液需开挖至基岩底板，因此收液系统天然底板通常渗透性较差且易于污染控制，按照一般防渗要求进行防渗即可。对于沟谷第四系覆盖层较厚的特殊地区可按重点防渗区要求进行防渗。对于车间工艺池体（浸出液池、除杂池、沉淀池、产品池、配液池、污水池等）、硫酸储罐区和污泥暂存区等需要长期连续使用的设施应按重点防渗区要求进行防渗，具体见表 4-4 和表 4-3。

表 4-4 地下水污染防渗分区判别依据

防渗分区	天然包气带防污性能	污染控制难易程度	污染物类型	防渗技术要求
重点防渗区	强	难	重金属、持久性有机物污染物	等效黏土防渗层 Mb≥6.0m，渗透系数 K≤1.0×10^{-7}cm/s；或参照 GB18598 执行。
	中-强	难		
	弱	易		
一般防渗区	弱	易-难	其他类型	等效黏土防渗层 Mb≥1.5m，K≤1×10^{-7}cm/s；或参照 GB16889 执行
	中-强	难		
	中	易	重金属、持久性有机物污染物	
	强	**易**		
简单防渗区	中-强	易	其他类型	一般地面硬化

表 4-5 地下水污染分区防渗及要求

序号	防渗分区	建（构）筑物	防渗要求
1	重点防渗区	车间和废水处理站工艺池体	等效黏土防渗层 Mb≥6.0m，防渗层结构渗透系数 $K \le 1.0 \times 10^{-7}$cm/s；或参照 GB 18598 执行
		硫酸储罐、污泥暂存间	
2	一般防渗区	收液巷道、集液沟、避水沟、排水沟、应急池、截渗坝	等效黏土防渗层 Mb≥1.5m，防渗层结构渗透系数 $K \le 1.0 \times 10^{-7}$cm/s；或参照 GB 16889 执行
		产品仓库和物料仓库	
3	简单防渗区	富集站道路、办公区域	一般地面硬化

离子型稀土矿原地浸矿浸采矿块是发生稀土浸出液和浸矿剂渗漏的重要区域，应对注液和收液系统的各设施逐一做好防渗处理，防渗的做法根据其结构和实际功能有所差异，施工技术参照《渠道防渗工程技术规范》GB/T 50600-2010，也可以通过铺设防渗篷布实现防渗功能。对于车间，需要进行防渗处理的是各类工艺池体，可以充分利用车间所在场地花岗岩基岩底板合理设置各工艺池体，并通过裂隙封堵和铺设防渗篷布达到防渗要求。根据防渗篷布防渗效果的实验测试，篷布平均厚度为 0.47mm，纵向撕破强力 96.6N，横向撕破强力 127.6N，垂直渗透系数小于 7.47×10^{-13}cm/s，耐静水压 0.5MPa，具有一定的机械强度和良好的防渗性能，试验过程中未出现防渗篷布撕裂和渗漏现象，效果良好，满足环保要求。

本标准提出离子型稀土矿生产企业应配置浸矿剂注入量和稀土浸出液回收量的计量装置和设施，根据稀土浸出液回收情况合理控制浸矿剂注液强度，在保障稀土开采回采率的基础上，从源头上尽可能减少浸矿剂的使用量。

本标准提出原地浸矿开采结束后应利用现有注液和收液系统对浸采区进行清水淋洗，收集的淋洗尾水回用到下一矿块配制浸矿剂，或利用污水处理站处理达标后排放。根据典型离子型性系统矿山试验项目淋洗结果，通过清水淋洗措施，可有效降低尾水中特征因子硫酸盐、镁离子和铅的浓度，其中硫酸盐浓度由 5437mg/L 降低至 514mg/L，镁离子浓度由 823mg/L 降低至 78mg/L，铅浓度由 1.14mg/L 降低至 0.2mg/L，尾水硫酸盐和总铅均满足水污染控制标准限值要求。

上述源头削减控制措施在赣州稀土试验项目和其他同类离子型稀土开采项目中均得到有效应用，措施有效且可行。

4.3.3 水污染过程监管预警措施

本标准提出离子型稀土矿开采企业应建立地表水环境和地下水环境动态监控体系。其中地表水环境监测断面包括地表水对照断面、污染监控断面、管控断面和环境质量达标断面。地下水环境监测井包括对照监测井、污染扩散监测井、环境影响跟踪监测井等。根据离子型稀土矿浸采矿块布置、地形条件、水系特征、地表水与地下水补排关系、环境敏感目标、水环境功能等，建立地表水环境和地下水环境动态监控体系，通过分析水质变化情况并结合水污染控制要求进行生产管理和污染防控。

按照 HJ91.2 要求进行地表水环境质量动态监测。原则上应布设至少 1 个对照断面，在每个实际浸采矿块下游 100 米、200 米位置分别布设污染监控断面，在每个矿区流出地表水与矿区边界相交处均应设置管控断面、在矿区流出支流汇入最近有水力联系的干流混合区外设置环境质量达标断面。

按照 HJ164、HJ610、HJ1209 等规范要求进行地下水环境质量动态监测。对照监测井应布设在矿区地下水流向上游处，尽可能不受矿山生产过程影响，原则上应布设至少 1 个，污染扩散监测井宜布设在矿区内浸采矿块下游 30~50m 处或地下水流势汇处，每个浸采矿块所在小流域内监测点数量不少于 3 个，环境影响跟踪监测井可选取矿区外可能受影响的具有供水意义的民井、天然泉点和地下水环境监测井，监测点数量宜根据可能受影响范围进行确定。

本标准提出离子型稀土矿开采企业宜建立水环境分区分质管理体系，根据水质类型分别进行回用或处理后达标排放。同时，建议构建稀土矿区水环境监测和台账管理制度，落实专人负责。由于离子型稀土矿区地表水和地下水环境动态监控体系对矿区的污染防控具有重要的意义，鼓励采用水环境自动监测设施和智慧环保管理系统平台，提高水环境数字化智能化管控能力。

4.3.4 水污染末端风险防控措施

本标准提出水污染末端风险防控措施主要包括在浸采矿块和车间下游设置应急池、在注液矿块所在沟谷设置截水坝、在浸采区收液系统外侧设置环保回收井、在矿块小流域垭口处设置地下水抽提系统、在矿区内配套建设相当规模的污水处理设施等，并给出了相应的要求。

其中，应急池主要收集和暂存事故状态下泄漏的浸出液和尾水；截渗坝主要用于拦截矿块附近受污染溪流地表水体，通过启用拦截坝将超标水体抽回至污水

处理站处理或回用配液工段；环保回收井主要利用水力截获原理回收浸采区未进入收液系统渗漏流失的稀土浸出液和浸矿剂，通常在集液沟外侧地势低洼处按一定间距进行布设；污水处理设施主要用于将渗漏尾水、受污染地表水和地下水、浸采区淋洗阶段尾水的处理，处理后的尾水优先进行生产回用，向外环境排放的应符合相应的水污染排放控制要求。

地下水抽提系统包括上下游地下水监测井和地下水抽提井，当上游监测井发现地下水水质恶化且接近地下水风险管控目标时，启动地下水抽提井进行抽水，形成局部地下水漏斗区，利用水力截获将受污染的地下水从含水层中抽取到地面加以处理。地下水抽提系统布设原则：

①环境保护敏感点及地下水使用功能。通常在稀土矿区外部敏感点有地下水使用功能的区域之前设置地下水抽提系统，避免对使用的地下水环境产生影响；

②水文地质条件。由于矿区内地下水均补给地表水体，此范围内设置地下水抽提系统意义不大，应在出矿区后地表水补给第四系松散岩类孔隙水的地段设置地下水抽提系统，才能进一步阻止地下水的迁移途径；

③地表水系交汇情况。综合考虑矿区外溪流交汇情况，若存在矿区内溪流与另一支流在矿区外交汇，那么地下水抽提系统应布置在交汇口下游合适地段；

④地形条件及地下水截获难易程度。稀土矿区山脉错综复杂，应根据矿区外山体走向来确定地下水截获工作的难易程度，若出矿区一定范围山体走向逐渐合拢，且存在明显第四系，可在龙口设置地下水抽提系统，确保受影响地下水被进一步完全截获，从而提高地下水抽提系统的最大使用功能。

4.4 监测要求

本标准控制污染物的采样频次和时间，根据离子型稀土矿原地浸矿工艺特点，考虑离子型稀土矿山原地浸矿开采过程中非点源污染，对地表水、地下水提出监测频次要求。

矿山开采期，地表水对照监测断面水质监测频次不少于 1 次/季度；在开采矿块周边地表水设置若干污染监控断面，水质监测频次不少于 1 次/周；管控断面和地表水环境质量达标断面水质监测频次不少于 1 次/月。

矿山开采期，地下水对照监测井水质监测频次不少于 3 次/年，丰、平、枯水期至少各 1 次；污染扩散监测井水质监测频次不少于 1 次/月；环境影响跟踪监测井水质监测频次不少于 1 次/季度。注液结束后，根据尾水收集及水质监测结

果变化情况可逐步减少监测频次。

本标准所列各控制污染物的测定方法，国家及行业均已颁布相应的标准，详见标准文本的表 4。

5 与现行相关法律、法规、规章及相关标准，特别是强制性标准的协调性

本标准（审定稿）符合现行法律、法规、规章及相关标准。

6 标准中涉及的专业或知识产权说明

本标准制定过程中未检索到专利和知识产权问题。

7 标准作为强制性或推荐性标准的建议

建议该标准作为强制性标准。

8 贯彻标准的要求和措施建议

本标准规定了采用原地浸矿工艺的离子型稀土矿开采水污染控制要求和控制措施，建议用于采用原地浸矿工艺的离子型稀土矿开采企业水污染控制管理，建设项目的环境影响评价、环境保护设施设计、竣工环保验收、排污许可证核发及其投产后的水污染控制管理。