

Case Report

Environmental Sustainability of Open-Pit Coal Mining Practices at Baganuur, Mongolia

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Abstract: In this paper, we studied one of the largest coal mines in Mongolia, the Baganuur Coal Mine, in terms of environmental sustainability related to mining practices, with a focus on discharged water and waste sediments. The present quality and potential for future pollution were assessed. Based on World Health Organization and Mongolian guidelines, groundwater pumped from the mining operations could be used for drinking and domestic purposes. In addition, based on the Na absorption ratio, groundwater samples from GW-2 and GW-3 could be used as agriculture water supplies with salinity reduction, or used to grow halophytes as a measure for desertification control and pasture production. All waste soil samples appeared to have a desertification potential. Dust particles smaller than 150 µm comprised more than 80% of soil samples, which had arsenic levels higher than the Mongolian soil pollution standards. In addition, soil collected between coal seams (S-5) showed high sulphur content based on X-ray fluorescence (XRF) and scanning electron microscopy–energy dispersive X-ray (SEM-EDX) spectroscopy analyses, strong potential for producing acid mine drainage in the analysis of pH of net acid generation and net acid production potential, and potential for leaching of metals, such as Co. Therefore, the Baganuur Coal Mine requires soil pollution control measures to mitigate the risks of dust and desertification. In this perspective, mine groundwater could be used to reduce environmental stresses by supporting pasture crops such as halophytes on waste disposal sites, thereby preventing dust issues and desertification. Continuous efforts, including monitoring and enacting environmental management measures, are needed from both the mining company and the government to ensure sustainable mine development.

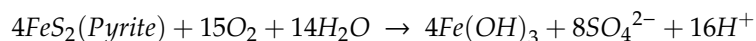
Keywords: Baganuur coal mine; environmental sustainability; soil pollution; water quality

1. Introduction

Development and the subsequent increase in standard of living worldwide have resulted in elevated demands for raw materials and ores [1]. Thus, greater exploitation of natural resources through mining is needed. In terms of natural mineral resources, Mongolia is one of the richest countries in the world, and mining is the country's main industry, accounting for 60% of its gross industrial output [2]. However, mining processes can cause various environmental problems, including deforestation, soil erosion, destruction of the natural landscape, landslides, water-level reduction and surface water depletion through dewatering, as well as water and soil pollution from mining waste and tailing dust [3–7].

Through natural weathering processes driven by rain and wind, waste rocks and overburden can be direct sources of pollution [8,9]. Acid mine drainage (AMD) occurs when pyrite and sulphide

minerals make contact with water and oxygen in the air, producing acid ($[H^+]$) through the following reaction [10–13]:



These acids act as solutes, causing leaching of metals from the waste and increasing the potential for subsequent water and soil contamination through dissolution and precipitation processes of secondary minerals [12–16]. Therefore, environmental management systems must be implemented to prevent and mitigate various environmental issues and improve the sustainability of both the mining industry and the communities living in mining areas.

Two types of mining techniques are used: Open-pit mining and underground mining. Open-pit mining includes blasting of soil and vegetation to access underground ore layers or coal seams [17]. Consequently, this method produces large volumes of mining waste, including soil and overburden, which increase the vulnerability of mining environments to soil erosion and pollution. The Baganuur Coal Mine was first excavated as an open-pit mine in 1978. It is one of the largest coal mines in Mongolia, covering about 60 km², and supplies mostly to the power plants in Ulaanbaatar, the capital city of Mongolia. The Baganuur Coal Mine Expansion Feasibility Study [18] reported that, based on the amount of coal mined to date (over 100 Mt) and the amount of identified reserves as of 2015 (812 Mt) mining can continue for at least several decades.

Over the 40 years since 1978, the amounts of waste soil and groundwater pumping rate were 337 Mbcm and 1100 m³/h, respectively. Of the discharged water, 49% is supplied to the local power plant, 21% to a nearby lake and 30% onto fields. Considering the continuing exploitation of coal in the mine, the amounts of waste soil and groundwater pumping generated will be enormous, and could be limiting factors for the sustainable development of the mine due to environmental degradation in the surrounding area. Therefore, it is important to understand the present status of the impact on the environment to plan for sustainable development in the future. The objectives of the present study were to assess the pollution potential of the water and soil environment based on field data and to provide options for sustainable development of the Baganuur Coal Mine and nearby areas.

2. Materials and Methods

2.1. Study Area

Baganuur (N 47°43′12.5″ E 108°18′51.1″) is located about 130 km east of Ulaanbaatar, at an elevation of 1333–1376 m above sea level (www.baganuurmine.mn). It has a cold, dry climate with an annual mean precipitation of 288 mm and extreme temperatures in summer and winter of −24.2 and 16.5 °C (Figure 1). The topography of the area is characterised by wide valleys, which are bounded by small hilly mountains to the west and east. The main river system is the Kherlen River, flowing north to south (inset, Figure 1).

Geologically, the Baganuur Coal Basin is part of the larger Choir Nyalga Coal Basin, which is a rift-type basin with fluvial-swamp, fluvial-lacustrine, deltaic-fluvial, and fluvial sediments. The direction of the basin axis is southwest–northeast. The Baganuur Basin is filled with Jurassic and Cretaceous sediments overlain with Quaternary alluvial, deluvial, and aeolian sediments [19]. The Khukhteeg formation consists of conglomerate, gravel, sand, silt, and brown coal with an average thickness of 450 m. Three major coal seams are exposed within the Cretaceous clastic sedimentary layers, which have a synclinal structure in the north-northeast–south-southwest direction. The width and length of these layers are 3 and 8 km, respectively, and their thickness ranges from 4 to 25 m, with an average of 15 m [20]. A Quaternary sand and gravel layer of 6 m thickness covers the clastic sedimentary rock. Regional groundwater flows from the Khentii Mountains in the northwest toward the southeast across the mining area (www.baganuurmine.mn).

The mine site consists of mining pits, offices, and associated infrastructure. The mine is dewatered with advance dewatering bores supported by in-pit sump pumping. The dewatering product is piped

away from the mine site to the Baganuur thermal plant and local surface waterways. The mine's portable water supply is provided by the public water supply bores of Baganuur Water LLC. Wastewater discharge is piped to the district wastewater treatment plant.

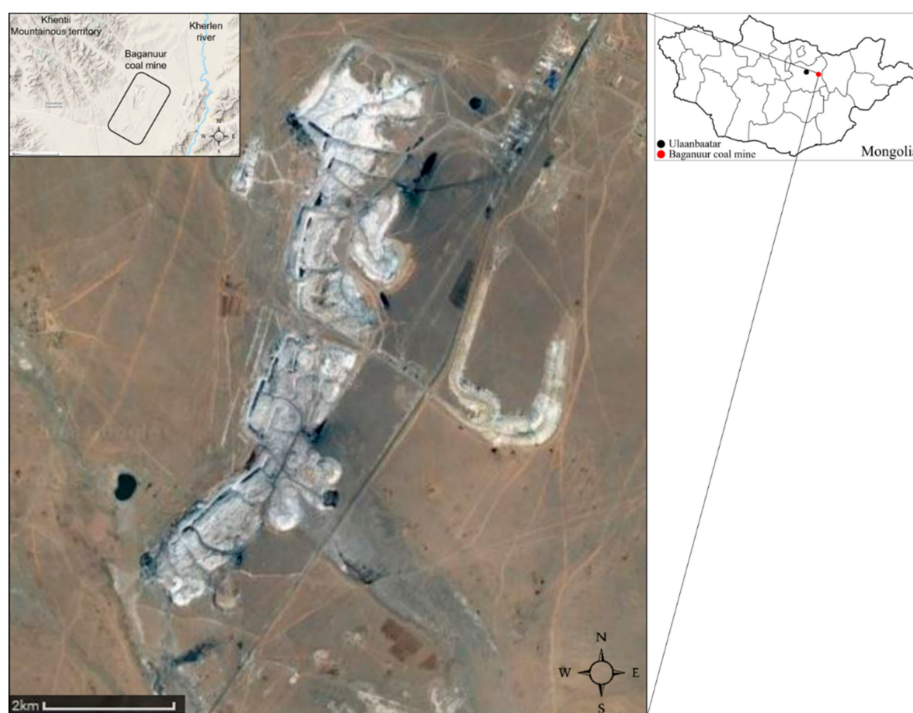


Figure 1. Location of the Baganuur Coal Mine in Mongolia (photos adapted from Google).

2.2. Sampling and Field Study

Geochemical information of water and soil in the mining area would be useful for understanding the waste characteristics of inorganic contaminants and the generation of acid mine drainage [21]. The field survey and sampling campaigns were carried out in October 2017 and May 2018 by teams from Yonsei University (Seoul, Korea), and Mongolian University of Science and Technology (Ulaanbaatar, Mongolia). Since the Baganuur Coal Mine is in operation, water and soil sampling were performed with the guidance and cooperation of mine staff.

Water samples were collected from ten points, including groundwater from the dewatering system (GW-1, -2, -3, -4, and -5), discharged water (DW-1 and -2), the collection station (CS), lake, and sump water (SW) (Table A1, available in Appendix A). The depths of the dewatering wells were 180 (GW-1), 226 (GW-2), 270 (GW-3), 240 (GW-4), and 260 m (GW-5). Water samples were filtered through 0.45 μm membrane filters and then preserved for laboratory analysis of cations and anions in polypropylene bottles. Samples for cation and metal analysis were preserved by the addition of concentrated nitric acid to a lower solution pH below 2, and those for the anion analysis were refrigerated after filtration [22,23]. On site, water samples were measured for electrical conductivity (EC; $\mu\text{S}/\text{cm}$), dissolved oxygen content (mg/L), oxidation–reduction potential (mV), pH, and temperature using a portable multi-probe (Orion Star A329; Thermo Scientific). Alkalinity was measured using the acid titration method.

Five soil samples were collected, including waste soil (S-1 and -2), background soil (S-3), soil collected near the sump water (S-4), and soil collected between coal seams (S-5) (Table A1). For sampling, the top soil layer of about 10 cm was removed in $2 \times 2 \text{ m}^2$ area, and then soil samples were obtained by mixing soils from the next 15 cm of depth collected at five points in plastic bags [24]. Soil samples represent the areas of approximately $300 \times 300 \text{ m}^2$ (S-1), $300 \times 1000 \text{ m}^2$ (S-2), $100 \times 200 \text{ m}^2$ (S-4), and $100 \times 200 \text{ m}^2$ (S-5), respectively, in the study area.

2.3. Laboratory Analysis

In the water samples, cations (Na, K, Ca, Mg, Fe, Mn, Si, Al, As, Cr, Co, Cu, Mo, Ni, Rb, Sr, V, Zn, Li, B, Pb, Ag, and Cd) and anions (Cl, SO₄, NO₃, Br, and F) were analysed using inductively coupled plasma-optical emission spectrometry (ICP-OES; iCAP 7000; Thermo Scientific, Waltham, MA, USA) and ion chromatography (IC; 883 Basic IC plus, Metrohm, Herisau, Switzerland), respectively, at the groundwater laboratory of Yonsei University. The analytical results were checked for electrical neutrality, and results with charge balance errors of less than 10% were used for further interpretation [25]. Data analysis was conducted using the Aquachem program version 2014.2 (Waterloo Hydrogeologic, Waterloo, ON, Canada) for chemical plots and SPSS version 24 (IBM Corp., Armonk, NY, USA) for statistical analysis.

Soil samples were analysed after drying. Particles less than 2 mm in diameter were analysed with a laser-based particle size analyser (Mastersizer 2000; Malvern Instruments, Malvern, UK). To elucidate their mineral and chemical compositions, they were also ground and analysed using X-ray fluorescence (XRF; PW2404; PHILIPS, Amsterdam, The Netherlands), X-ray diffraction (XRD; Miniplex II, Rigaku, Tokyo, Japan), and scanning electron microscopy (JSM-5610LV; JEOL, Tokyo, Japan) with energy dispersive X-ray spectroscopy (Oxford Instruments, Abingdon, UK) (SEM-EDX) at Yonsei University. To assess the environmental risk from mine dust, the heavy metal contents of dust-sized particles from soil samples were acid digested and analysed using ICP-OES following standard methods [26,27].

Potential of samples to leach metals from rocks and soils in mining wastes were evaluated through leaching tests following the ASTM D4793-09 method (Standard Test Method for Sequential Batch Extraction of Waste with Water). This method requires mixing 50 g of dry soil with 1 L of distilled water for 18 h and then filtering the mixture through a 0.45 µm membrane filter. The remaining slurry is mixed with a further 1 L of distilled water; this filtering procedure was carried out four times. The filtrates were analysed using ICP-OES and IC for cations and anions, respectively [28,29].

Recent studies have suggested that changes in the particle size distribution (PSD) provide useful indicators of soils that require management or are subject to erosion or desertification [30]. Thus, to assess the desertification potential of this site, the fractal dimension (D_m) of PSD was calculated as follows [31]:

$$\frac{V(r < R_i)}{V_T} = \left(\frac{R_i}{R_{\max}} \right)^{3-D_m}$$

where r is the particle size, R_i is the particle size for grade i in the particle size grading, $V(r < R_i)$ is the volume of soil particles of diameter less than R_i , V_T is the total volume of soil particles, and R_{\max} is the maximum diameter of soil particles.

The soil particle content was sorted by particle size at various soil levels and a diagram was plotted using $\log\left(\frac{V(r < R_i)}{V_T}\right)$ as the ordinate, $\log\left(\frac{R_i}{R_{\max}}\right)$ as the abscissa. Then, a linear fit to the data was estimated with the slope of $3 D_m$. Subsequently, the fractal dimension (D_m) becomes 3 slope [31,32].

3. Results and Discussion

3.1. Hydrogeochemical Characteristics of Water

Water samples from the Baganuur Coal Mine had a pH of 6.63–9.02 and EC of 535–1703 µS/cm (Table A2). Based on their total dissolved solids (TDS) contents, GW-2, -3, -4, -5, DW-2, lake, and SW were freshwater (TDS < 1000 mg/L), while GW-1 and DW-1 were brackish, with relatively high TDS of 1145–1703 mg/L [33]. Spatiotemporal variations in basic water chemistry were evaluated using the Stiff diagram method (Figure 2). Water samples showed two dominant types: Na-HCO₃ and Ca-HCO₃. One sample, GW-4, showed a change in water types, from Na-HCO₃ in October to Ca-HCO₃ in May. Changes in major water composition could be derived from various reasons such as changes of hydrochemical reactions following flow-path changes due to mining stages, implying that long-term monitoring is warranted.

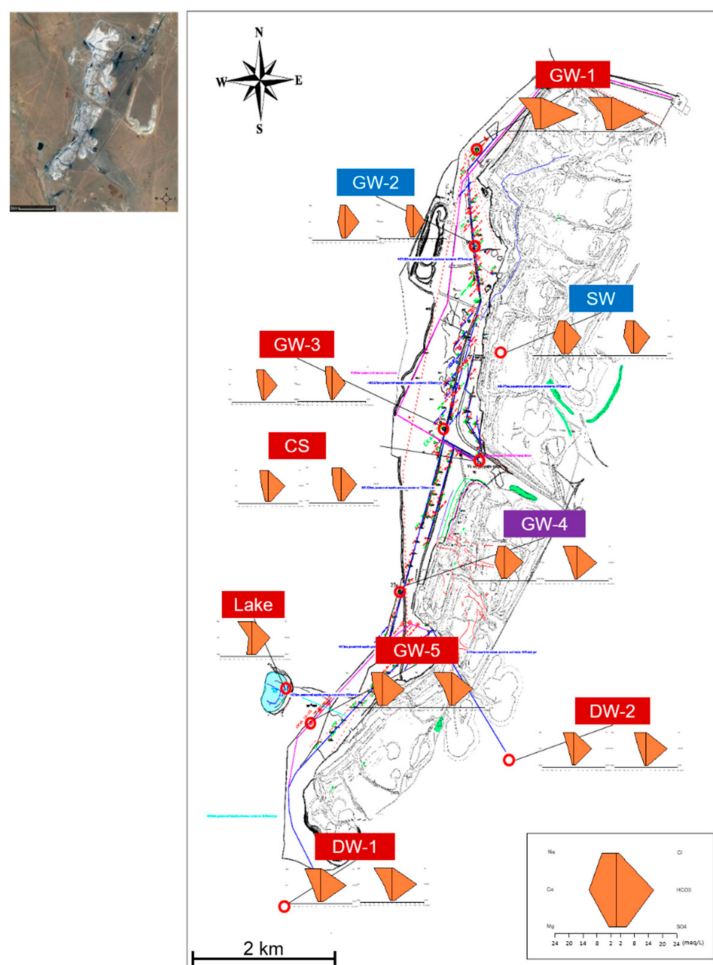


Figure 2. Stiff diagrams of water samples collected in October 2017 (left) and May 2018 (right). Sample numbers in red and blue boxes indicate Na-HCO₃-type and Ca-HCO₃-type water, respectively. The purple box indicates a sample that changed type over time.

Hydrogeochemical processes were deduced based on the composition of 2017 and 2018 water samples using statistical methods, including factor analysis and Pearson correlation analysis. All water samples had Na/Cl and HCO₃/SiO₂ ratios greater than 1 and 10, respectively. In addition, except for the lake sample, the samples had Ca/SO₄ ratios exceeding 0.5 (Table A3). These results indicate that carbonate dissolution has a stronger impact on water composition than silicate weathering.

Factor analysis showed that 70% (October 2017) or 75% (May 2018) of sample variation was affected by two major factors (Table A4). The first factor was associated with Na, K, Ca, and Mg among cations and HCO₃ among anions, explaining 44% and 46% of the compositional variance in 2017 and 2018, respectively. Considering the natural environment of the mine formed in the lake depositional environment in the dry climate, the dominant weathering process generated these compositions appeared to be the dissolution of carbonate minerals such as calcite, dolomite, trona (NaHCO₃·Na₂CO₃), natron (Na₂CO₃·10H₂O), and nahcolite (NaHCO₃) [25,34]. The second factor was related to SO₄ and NO₃, and explained 25% and 29% of sample variance in 2017 and 2018, respectively. SO₄ and NO₃ showed positive correlations with Ca (Tables A5 and A6). Therefore, the source of SO₄ could be attributed to dissolution of sulphate minerals such as anhydrite (CaSO₄) and gypsum (CaSO₄·2H₂O) and that of NO₃ to a compound used in mining explosives, Ca(NO₃)₂ [35]. In summary, the chemical composition of water at the Baganuur Coal Mine appeared to be driven primarily by the dissolution of carbonate and sulphate, with a secondary influence of explosive residue.

3.2. Water Quality and Pollution Potential

In Mongolia, surface water does not provide sufficient water supply because of climate conditions. For residents of the Baganuur area, groundwater is the principal source of water, and water is also pumped from the nearby Kherlen River, located 13 km east of the mining area. Considering the continuous water level decline occurring due to dewatering during the mining process, recycling of water removed from the mine could benefit the local residents through reduction of the groundwater pumping cost, lessening of the potential for land subsidence and preserving valuable water resources for sustainable management of the local environment [4,5].

Compared with the Mongolian water pollution standard [36] and World Health Organization (WHO) drinking water guidelines [37] (Table A7), all samples had concentrations of water quality parameters below the WHO guideline levels. However, some components, such as Fe, exceeded Mongolian standards in GW-1, -2, -3, -4, -5, and CS. Discharged lake water had pH and K levels above the Mongolian standard. Na and K also exceeded the standard in SW and GW-1, respectively. DW-1 and -2, representing about 30% of the total dewatering water, met the WHO and Mongolian quality standards. Thus, water from these wells could be used as a drinking and domestic water resource while supporting mine operations.

3.3. Salinity Hazard

In arid and semi-arid areas, the salinity and sodicity of water can inhibit the growth of crops and other plants [38]. To evaluate the potential effects of recycling water from mining for agricultural usage, the salinity and Na hazards were estimated using the Na adsorption ratio (SAR) and EC (Figure 3). The SAR reflects the ratio of cation exchange processes involving Na in water to those of Ca and Mg in soil, and is calculated as:

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}}$$

where ionic concentrations are in units of meq/L [39,40].

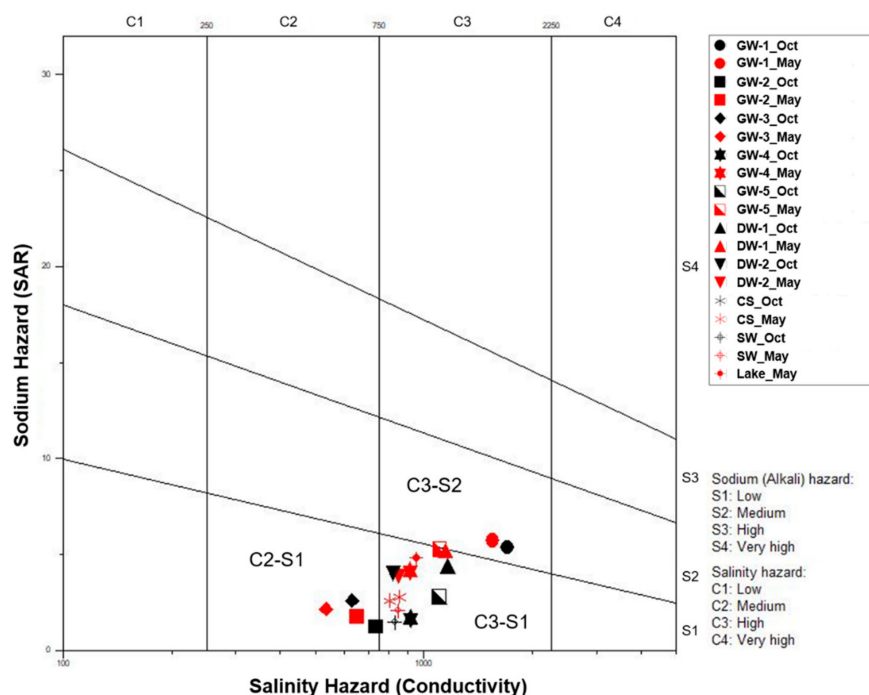


Figure 3. Wilcox diagram for the classification of irrigation waters (GW: Groundwater; DW: Discharge water; CS: Collection station; SW: Sump water).

From the Wilcox plot displayed in Figure 3, the water samples showed medium to high salinity hazard and low Na hazard. GW-1 water shows high salinity and medium Na hazard, while GW-2 and -3 had medium salinity and low Na hazards. Other water samples show high salinity and low Na hazards. Thus, if salinity can be reduced, the mine water could safely be used for local agriculture. If not, the water could be used to grow halophytes for animal fodder, as reported by Le Hou erou et al. [41] and El Shaer et al. [42], to prevent desertification and reclaim the area of overburden deposition from the open-pit mine [43]. The agriculture and stock-farming industries in Mongolia account for 12% of the gross domestic product, with pastures accounting for 98% of cropland and 75% of the country's total area [2]. Therefore, if its wastewater can be used to support pastures and the growth of halophytes, the mining process could contribute to sustainable management of the local environment.

3.4. Acid Generation Potential

AMD is a common issue in mining areas that can cause dissolution of metal components from waste soils and sediments, leading to secondary contamination due to precipitation of common Fe oxyhydroxides along waterways [14,44]. Thus, the AMD potential of soil samples was assessed through analysis of pH, XRD, XRF, and SEM-EDX results.

The main components of the sampled soils were quartz, microcline and albite, and no sulphide minerals that could cause AMD were identified in XRD analysis. However, soil sample S-5, which was collected between the coal seams (Figure 4), was acidic (pH: 2.77) (Table 1). S-5 had a sulphur content of 0.37% based on XRF analysis, higher than other soils, as well as a sulphur level of 0.58% based on SEM-EDX analysis, which was not detected in other samples (Table 2). The low pH of S-5 could be attributed to acid-generating reactions of its sulphur components [9,45–48].

The acid generation potential of sample S-5 was quantified to evaluate the AMD potential using plots of pH of net acid generation (NAG_{pH}) versus net acid production potential (NAPP). The average NAG_{pH} was 2.98 (2.97–3.00) and the average NAPP was 8.67 kg H_2SO_4 /ton (8.08–9.30 kg H_2SO_4 /ton). An NAG_{pH} value below 4.5 with significant NAPP indicates that a sample has sufficient acid generation potential for the AMD process (Figure A3) [47,48].

Table 1. pH and XRF results of soil samples.

Sample	pH	Weight (%)																	
		Si	Al	Fe	K	Ca	Na	Ti	Mg	P	Mn	S	Zr	Cr	Rb	Zn	Sr	Cu	Au
S-1	7.10	67.7	12.4	7.49	7.38	1.77	1.04	1.02	0.48	0.17	0.12	0.09	0.08	0.07	0.06	0.05	0.04	ND	ND
S-2	6.17	70.1	11.7	5.73	8.39	1.16	0.81	1.03	0.41	0.18	0.13	0.04	0.08	ND	0.05	0.04	0.04	0.09	ND
S-3	6.44	69.1	11.7	6.10	6.33	2.75	2.01	0.97	0.45	0.13	0.18	ND	0.09	0.06	0.05	0.03	0.09	ND	ND
S-4	7.50	65.5	13.5	8.38	6.90	2.00	1.07	1.01	0.77	0.19	0.15	0.14	0.09	0.07	0.06	0.03	0.05	0.06	0.04
S-5	2.77	71.9	11.7	4.59	7.99	1.07	1.10	0.63	0.32	0.09	0.08	0.37	0.06	ND	0.04	ND	0.04	ND	ND

ND indicates no detection.

Table 2. SEM-EDX results of soil samples.

Sample	Weight (%)													
	O	Si	Al	Fe	Mg	Ca	K	Na	Ti	S	Cu	Zn	B	
S-1	48.38	32.64	8.80	3.93	0.47	0.69	3.07	1.01	1.02	ND	ND	ND	ND	
S-2	48.65	32.35	9.71	3.05	0.81	0.67	3.18	0.71	0.88	ND	ND	ND	ND	
S-3	47.71	32.42	7.97	4.91	0.86	1.04	3.32	1.76	ND	ND	ND	ND	ND	
S-4	62.58	8.96	3.35	1.42	0.31	0.27	0.70	0.26	ND	ND	0.37	ND	21.78	
S-5	48.34	31.96	9.11	3.41	0.39	ND	3.47	1.12	0.54	0.58	ND	1.09	ND	

ND indicates no detection.

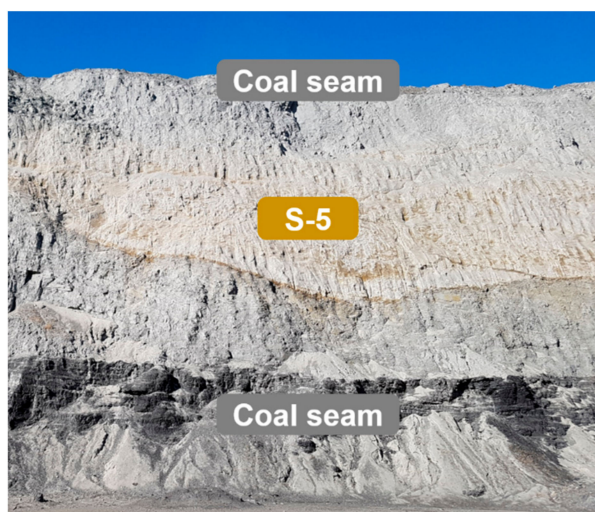


Figure 4. Soil sampling site between coal seams (S-5).

3.5. Potential for Metal Leaching

Metals in the mineral phase in waste sediments and soils can be dissolved in acidic water, such as AMD. When the solution's pH increases, dissolved metals can be re-precipitated in secondary mineral phases or sorbed onto solid surfaces, posing a risk as a potential source of water and soil pollution [14,44].

Soil samples were evaluated for the pollution potential due to leaching of metal contaminants through leaching tests following a standard method [29]. Figure 5 shows the results of soil pH changes over four consecutive leaching tests. The pH measurements of soil samples S-1, -2, -3, and -4 (range: 5.63–7.19) were higher than that of distilled water blanks (range: 5.38–5.86), and the soil pH fell slightly during the tests. The pH of S-5 (range: 3.29–4.26) was much lower than those of other samples, and increased over repeated tests, indicating decreased levels of acid-generating materials.

From the leaching tests using 1 kg of soil, the total amount of SO_4 in sample S-5 was 4019.07 mg/kg, and those in S-1, -2, -3, and -4 were 34.03, 210.95, 3.27, and 75.93 mg/kg, respectively (Figure A4). The amount of SO_4 leached and pH showed a negative correlation ($r = 0.590$, significant at the 99% level), indicating that oxidation of sulphur in soils contributed to the low soil pH.

Leaching tests detected Ni, Zn, and Co, whereas As, Cd, Cr, Cu, Pb, and V were below the detection limit of 0.2 mg/kg (Table 3). Mongolian soil pollution standards for Ni, Zn, and Co are 100, 150, and 40 mg/kg, respectively. All samples had Co concentrations in leachates exceeding the pollution standard. Notably, sample S-5 had a Co concentration of 803.12 mg/kg, about 20 times the standard. Among the soils and waste sediments of the Baganuur mine, only sample S-5, collected between coal seams, showed pollution potential in terms of acid generation and subsequent leaching of Co into the water and soil environments; therefore, such soil requires appropriate preventive measures for sustainable development.

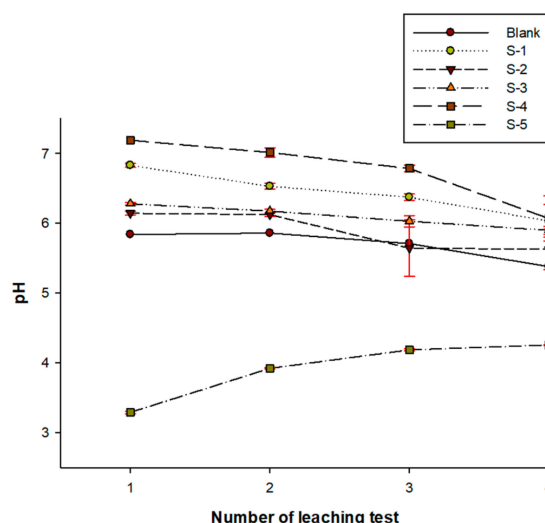


Figure 5. pH values from leaching tests of soil samples (x axis: Total four times of leaching test sequential process, y axis: Hydrogen ion concentration).

Table 3. Leaching test results for Ni, Zn, and Co.

Sample	Total Concentration (mg/kg \pm std.)		
	Ni	Zn	Co
Mongolian Soil pollution standards	100	150	40
S-1	BDL	1.29 (\pm 0.218)	54.61 (\pm 2.146)
S-2	BDL	0.89 (\pm 0.229)	73.94 (\pm 1.905)
S-3	BDL	BDL	54.77 (\pm 1.032)
S-4	BDL	0.74 (\pm 0.341)	144.53 (\pm 1.262)
S-5	1.10 (\pm 0.002)	5.74 (\pm 0.066)	803.12 (\pm 27.760)

* BDL indicates below detection limit (0.2 mg/kg).

3.6. Desertification Potential and Dust Generation

The open-pit coal mining process can degrade forests and prairies thereby accelerating desertification in areas with dry climates such as Mongolia. The PSD, soil texture, and D_m were evaluated (Table A8). The PSD showed that all soil samples consisted of more than 90% of fine materials, ranging from clay to fine sand. D_m is a desertification indicator, where a low D_m value indicates a higher desertification potential [32,49]. The D_m values of the soil samples ranged from 1.951 (\pm 0.053) to 2.288 (\pm 0.040), lower than the extreme desertification value of 2.298 (\pm 0.082) [49]. This result implies that mining in the Baganuur Coal Mine could have major impacts on the environment in terms of desertification.

Flying dust is generally described as particulate matter in the size range of 1–100 μ m [50], and Sapko et al. [51] reported that the mean particle size in coal mining areas is about 150 μ m. Human exposure to dust through the skin and inhalation can cause diseases such as pneumoconiosis, ischemic heart disease, and hard metal disease [50,52]. The PSD of soil samples of the Baganuur Coal Mine showed that more than 80% of the particles were smaller than 150 μ m. Furthermore, As concentrations in the dust (range: 5.57–14.17 mg/kg) exceeded the soil pollution standard in Mongolia of 4 mg/kg (Table 4). Since As is a carcinogen that can be absorbed into the body through skin exposure and inhalation [53,54], mine workers and residents living near the Baganuur Coal Mine are exposed to the risk of As poisoning. Consequently, measures should be implemented to prevent desertification and the generation of flying dusts for sustainable management of the mine.

Table 4. Composition of heavy metals in dust and Mongolian soil pollution standards [55].

Sample	Below 150 µm (%)	mg/kg ± std.										
		Pb	Cd	As	Cr	Sr	V	Cu	Ni	Co	Zn	Mo
Mongolian soil pollution standards		70	1.5	4	100	700	130	80	100	40	150	3
S-1	81.12	7.78 (±0.0404)	BDL	5.57 (±0.8549)	17.31 (±2.7260)	126.44 (±0.2.6625)	49.08 (±1.2806)	31.01 (±1.0242)	5.96 (±0.5925)	15.76 (±0.4448)	79.19 (±2.9052)	BDL
S-2	100	8.82 (±0.2377)	BDL	8.34 (±0.7712)	12.85 (±0.2536)	112.90 (±0.3851)	41.19 (±0.2778)	23.94 (±0.2830)	3.97 (±0.1614)	12.44 (±0.3044)	66.02 (±0.9377)	BDL
S-3	94.75	8.20 (±0.6163)	BDL	14.17 (±1.3766)	36.86 (±0.5023)	216.74 (±9.6837)	67.59 (±1.0617)	35.77 (±1.0971)	13.66 (±0.2380)	17.40 (±0.2621)	70.38 (±1.8438)	BDL
S-4	100	7.96 (±0.8396)	BDL	8.60 (±1.6423)	18.30 (±0.6441)	121.47 (±3.1256)	50.65 (±0.4425)	30.31 (±1.2879)	5.95 (±0.2543)	14.95 (±0.2383)	80.56 (±0.7366)	BDL
S-5	85.98	12.39 (±0.2861)	BDL	11.16 (±0.8664)	9.84 (±0.6902)	134.22 (±6.1592)	35.88 (±0.4203)	17.95 (±0.6403)	4.64 (±1.0600)	13.72 (±0.2693)	58.13 (±1.4714)	BDL

BDL indicates below detection limit (3 mg/kg).

3.7. Environmental Sustainability of the Baganuur Mining Practice

Scientific data are essential for sustainable development of the mining to decision makers. The results of this study show that availability of water as water resources, and environmental risk of soil including AMD, contaminated leachate, desertification, and the generation of dust. Considering the sedimentary depositional environment of the coal-bearing formations at this study area, the waste soil, similar to S-5, could be extended following the orientation of stratigraphy. Therefore, as a next step to quantify the AMD potential and associated risks to the surrounding environment, a more detailed study should be conducted with the concerted samplings of soil and water for the potential areas. Moreover, organic materials and bacteria (such as *T. ferrooxidans*), as well as Fe^{3+} , which can accelerate AMD and the release of heavy metals, should be analyzed because inorganic materials were only considered in this study [56]. The leaching test that could accommodate the fractionation of bioavailable phases should also be adopted [57,58]. Then, based on the detailed information, the proper or advanced tools for sustainable development and to support decision making could be proposed [59].

4. Conclusions

This study was carried out to assess the water and soil pollution potential of the Baganuur Coal Mine, one of the largest open-pit coal mines in Mongolia. Based on its enormous reserves, mining activity at this site is expected to continue for at least several decades; therefore, sustainable mining practices should be developed based on field monitoring data.

Water chemistry show that the sources of major ions, including Na, Ca, Mg, and HCO_3 , include carbonate weathering, dissolution of evaporite minerals, natural softening, and cation exchange processes. SO_4 and NO_3 could be generated from the dissolution of sulphate minerals such as anhydrite and gypsum, and from mining explosive residue, respectively. Compared with WHO drinking water guidelines and Mongolian water pollution standards, the waters represented by samples DW-1 and -2 appear to be suitable as domestic water resources. Thus, use of groundwater pumped from the mining area as a water supply could benefit local residents, who currently obtain water from the river 13 km away. In addition, based on SAR analysis, GW-2 and -3 could be used for agriculture water supply with salinity reduction or used to grow halophytes to control desertification, reclaim land, and provide pasture.

The textures of the sampled soils are generally silty loam or sandy loam with primary components of quartz, microcline, and albite. Waste soil that is excavated and removed during the mining process has desertification potentials, as determined through D_m calculation following PSD analysis. Furthermore, particles forming dust smaller than 150 μm comprise more than 80% of the soils, which have As levels above Mongolian soil pollution standards. The pH of soil samples ranged from 6.17 to 7.50, except sample S-5, which had a pH of 2.77.

S-5 was collected between coal seams and showed relatively high sulphur levels in XRF and SEM-EDX analysis, indicating the potential for AMD and subsequent metal leaching. Analysis of NAG_{pH} and NAPP showed that S-5 has potential for acid formation, and metal leaching tests confirmed acid generation, most likely from sulphide minerals based on the negative correlation between pH and leached SO_4 . S-5 also showed significant leaching of Co. When the upper coal seam is fully uncovered, then excavation of the second coal seam will start. Before this operation, the sediments of S-5 type should be removed and disposed as waste piles. It is the time the AMD and metal leaching could begin from the waste sediments exposed to the air and rainfall directly at land surface. Therefore, the Baganuur mine should carefully prepare the measures of safe disposal and prevention of environmental pollution.

In summary, water from the Baganuur Coal Mine could be used as a domestic water resource or for agricultural uses to support halophyte pasture crops and thus mitigate the risk of spreading As-containing dust. However, because sulphate and Co could be leached from the waste sediments, local water quality should be regularly monitored. Following the development of the mine, waste soil and discharged water will continue to increase, both in terms of the impacted area and the amount.

Therefore, continuous efforts, including monitoring and environmental management from both the mining company and the government, are needed to ensure sustainable development.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

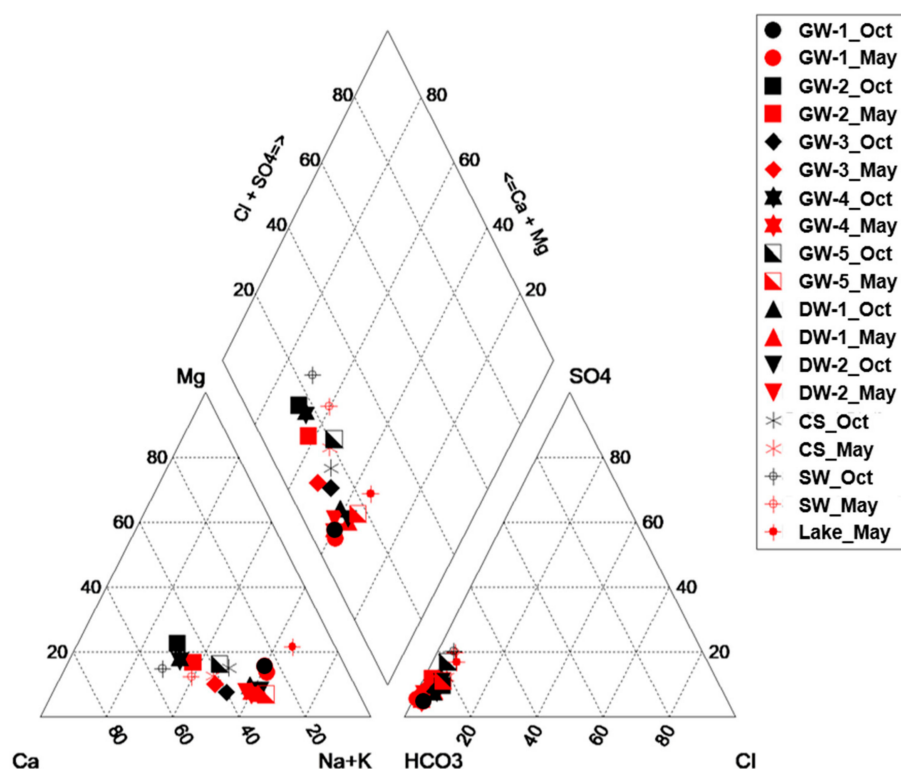


Figure A1. Piper diagram of water samples (GW: Groundwater; DW: Discharge water; CS: Collection station; SW: Sump water).



Figure A2. Sampling site for sump water (SW).

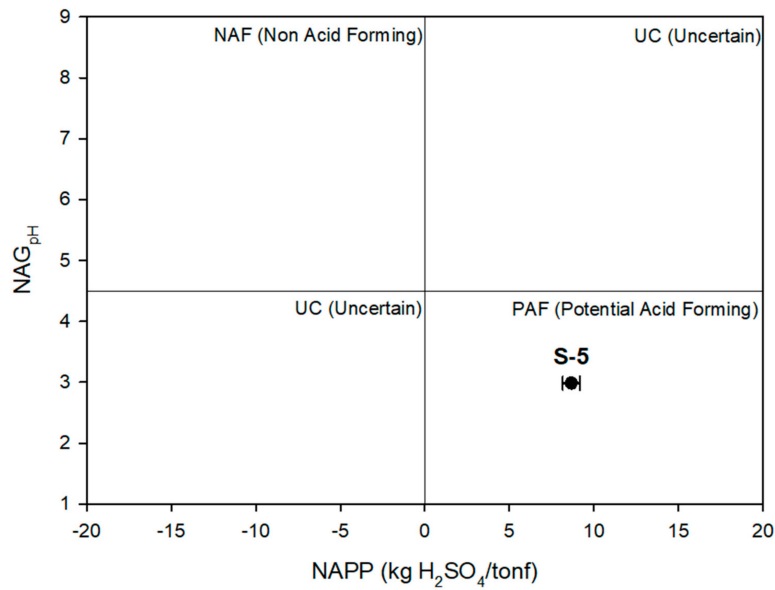


Figure A3. Assessment of the acid generation potential of soil sample S-5 collected between coal seams based on net acid generation pH (NAGpH) and net acid production potential (NAPP).

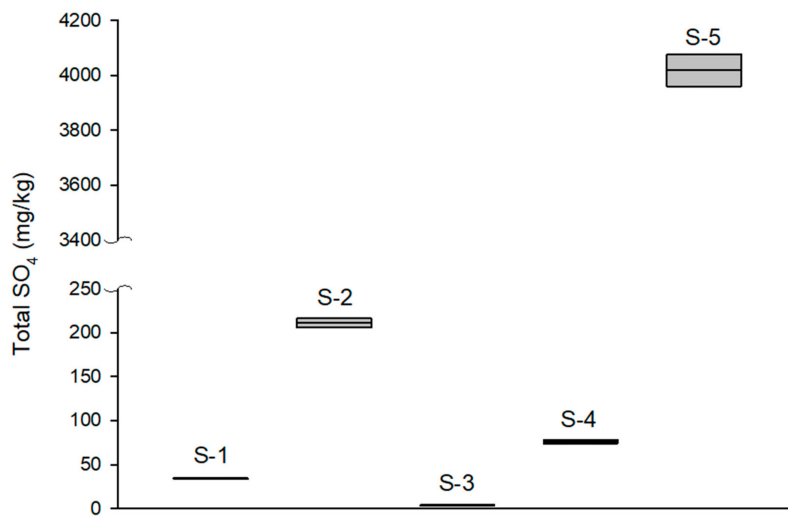


Figure A4. Total SO₄ concentration of the leachates.

Table A1. Sampling site of water and soil.

Sample	Latitude	Longitude
GW-1	N 47°45'08.3"	E 108°18'09.8"
GW-2	N 47°44'32.2"	E 108°18'07.0"
GW-3	N 47°43'18.8"	E 108°17'50.9"
GW-4	N 47°42'13.4"	E 108°17'23.5"
GW-5	N 47°41'22.1"	E 108°16'26.0"
DW-1	N 47°41'33.7"	E 108°16'05.3"
DW-2	N 47°43'49.8"	E 108°18'23.0"
CS	N 47°43'06.6"	E 108°18'13.2"
Lake	N 47°41'33.1"	E 108°16'05.3"
SW	N 47°43'49.7"	E 108°18'23.1"
S-1	N 47°45'21.3"	E 108°19'04.3"
S-2	N 47°44'25.3"	E 108°17'41.7"
S-3	N 47°44'15.9"	E 108°18'04.6"
S-4	N 47°44'25.2"	E 108°18'44.4"
S-5	N 47°42'45.3"	E 108°18'18.0"

Table A2. pH, EC, and major ion concentrations of water in October 2017 and May 2018.

Sample		pH	EC ($\mu\text{S/cm}$)	TDS (mg/L)	mg/L								
					Cl	HCO ₃	NO ₃	SO ₄	Na	K	Ca	Mg	SiO ₂
GW-1	Oct-2017	6.98	1703.0	1448.7	20.11	1026.83	1.89	41.80	223.13	6.52	79.77	31.00	18.84
	May-2018	6.85	1548.0	1372.3	7.36	951.55	BDL	44.33	237.29	5.96	83.33	28.23	17.61
GW-2	Oct-2017	6.63	736.5	566.3	17.73	380.23	1.99	34.13	41.01	3.00	58.11	16.86	18.53
	May-2018	6.93	652.2	490.3	5.37	300.50	BDL	32.46	59.18	2.96	63.68	14.15	17.62
GW-3	Oct-2017	7.29	632.4	550.2	12.75	368.03	BDL	26.08	72.19	2.71	48.95	5.63	26.01
	May-2018	7.07	535.2	511.2	4.15	352.35	BDL	24.91	59.55	2.65	46.92	6.87	25.31
GW-4	Oct-2017	6.92	916.7	780.6	20.16	514.43	2.48	55.76	65.41	2.98	85.53	18.89	22.41
	May-2018	7.18	914.9	804.1	9.51	550.55	BDL	23.07	132.64	3.15	63.56	8.67	22.18
GW-5	Oct-2017	7.02	1103.0	915.8	19.87	577.47	BDL	98.66	106.92	2.96	77.30	20.36	18.70
	May-2018	7.24	1105.0	917.7	24.82	565.06	BDL	59.63	176.07	2.58	67.63	10.25	15.18
DW-1	Oct-2017	7.30	1164.0	1024.9	22.29	691.33	BDL	49.39	158.54	2.86	75.57	14.09	17.39
	May-2018	7.26	1145.0	1029.6	22.68	676.18	BDL	49.24	182.89	2.74	75.67	11.37	15.44
DW-2	Oct-2017	7.48	822.4	727.0	20.43	494.10	BDL	32.89	112.52	2.29	46.73	7.85	17.42
	May-2018	7.40	850.0	524.5	8.51	573.97	BDL	35.48	122.53	2.56	62.67	8.70	17.22
CS	Oct-2017	8.11	854.8	733.2	14.06	479.87	BDL	53.36	92.96	4.20	59.73	15.38	23.37
	May-2018	8.29	801.3	677.2	19.67	416.22	BDL	49.46	91.20	3.34	73.03	13.51	20.08
Lake	Oct-2017	9.16	953.1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	May-2018	9.02	952.7	808.3	27.54	480.48	BDL	83.99	146.30	9.23	26.10	26.29	15.63
SW	Oct-2017	7.04	831.8	739.8	16.46	433.10	4.11	91.88	61.29	2.91	102.62	16.69	18.09
	May-2018	7.10	847.5	724.6	17.75	420.42	9.25	87.97	78.30	3.35	84.98	13.27	17.48

BDL indicates below detection limit (NO₃: 0.5 mg/L). ND indicates not detecting.

Table A3. Ratios for understanding water–rock interaction.

Sample		meq/L					mmol/L				Ratios			
		Na	K	Ca	Mg	Cl	HCO ₃	SO ₄	SiO ₂	$\frac{Na}{Cl}$	$\frac{Ca}{Ca+SO_4}$	$\frac{HCO_3}{SiO_2}$	$\frac{Mg}{Ca+Mg}$	$\frac{SiO_2}{Na+K-Cl}$
GW-1	Oct-2017	9.71	0.17	3.98	2.55	0.57	16.83	0.85	0.31	17.14	0.82	53.60	0.39	0.034
	May-2018	10.32	0.15	4.16	2.32	0.21	15.60	0.90	0.29	49.76	0.82	53.15	0.36	0.029
GW-2	Oct-2017	1.78	0.08	2.90	1.39	0.50	6.23	0.70	0.31	3.57	0.81	20.18	0.32	0.227
	May-2018	2.57	0.08	3.18	1.16	0.15	4.93	0.66	0.29	17.00	0.83	16.77	0.27	0.118
GW-3	Oct-2017	3.14	0.07	2.44	0.46	0.36	6.03	0.53	0.43	8.74	0.82	13.92	0.16	0.152
	May-2018	2.59	0.07	2.34	0.57	0.12	5.78	0.51	0.42	22.16	0.82	13.69	0.19	0.166
GW-4	Oct-2017	2.85	0.08	4.27	1.55	0.57	8.43	1.14	0.37	5.01	0.79	22.58	0.27	0.159
	May-2018	5.77	0.08	3.17	0.71	0.27	9.03	0.47	0.37	21.53	0.87	24.41	0.18	0.066
GW-5	Oct-2017	4.65	0.08	3.86	1.68	0.56	9.47	2.01	0.31	8.31	0.66	30.38	0.30	0.075
	May-2018	7.66	0.07	3.37	0.84	0.70	9.26	1.22	0.25	10.96	0.73	36.60	0.20	0.036
DW-1	Oct-2017	6.90	0.07	3.77	1.16	0.63	11.33	1.01	0.29	10.99	0.79	39.11	0.24	0.046
	May-2018	7.96	0.07	3.78	0.94	0.64	11.08	1.00	0.26	12.45	0.79	43.08	0.20	0.035
DW-2	Oct-2017	4.89	0.06	2.33	0.65	0.58	8.10	0.67	0.29	8.51	0.78	27.90	0.22	0.066
	May-2018	5.33	0.07	3.13	0.72	0.24	9.41	0.72	0.29	22.23	0.81	32.78	0.19	0.056
CS	Oct-2017	4.04	0.11	2.98	1.27	0.40	7.87	1.09	0.39	10.21	0.73	20.20	0.30	0.104
	May-2018	3.97	0.09	3.64	1.11	0.55	6.82	1.01	0.33	7.16	0.78	20.39	0.23	0.096
Lake	Oct-2017	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	May-2018	6.36	0.24	1.30	2.16	0.78	7.88	1.71	0.26	8.20	0.43	30.24	0.62	0.045
SW	Oct-2017	2.67	0.07	5.12	1.37	0.46	7.10	1.88	0.30	5.75	0.73	23.55	0.21	0.132
	May-2018	3.41	0.09	4.24	1.09	0.50	6.89	1.80	0.29	6.81	0.70	23.66	0.20	0.097

ND indicates not detecting.

Table A7. Composition of the water samples comparing with WHO drinking water guideline values [37] and Mongolian water pollution standard [36].

Sample	pH	mg/L																				
		Na	K	Ca	Mg	Fe	Mn	Cu	Ni	As	Pb	Cd	Cr	Zn	B	Mo	Co	F	Cl	NO ₃	SO ₄	
WHO drinking water guideline values	-	-	-	-	-	-	-	2.00	0.07	0.01	0.01	0.003	0.05	-	2.4	-	-	1.5	-	50	-	
Mongolian water pollution standards	6.5–8.5	200	8	100	30	0.3	0.4	0.01	0.01	0.01	0.01	0.005	0.01	0.01	-	0.25	0.01	1.5	350	50	500	
GW-1	Oct-2017	6.98	223	6.52	79.8	31.0	4.90	0.09	BDL	BDL	BDL	BDL	ND	BDL	BDL	ND	BDL	BDL	0.75	20.11	1.89	41.80
	May-2018	6.85	237	5.96	83.3	28.2	2.51	0.07	BDL	BDL	BDL	BDL	ND	BDL	BDL	BDL	BDL	BDL	0.37	7.36	BDL	44.33
GW-2	Oct-2017	6.63	41.0	3.00	58.1	16.9	2.67	0.09	BDL	BDL	BDL	BDL	ND	BDL	BDL	ND	BDL	BDL	0.66	17.73	1.99	34.13
	May-2018	6.93	59.2	2.96	63.7	14.2	2.15	0.07	BDL	BDL	BDL	BDL	ND	BDL	BDL	BDL	BDL	BDL	0.37	5.37	BDL	32.46
GW-3	Oct-2017	7.29	72.2	2.71	48.9	5.63	0.48	0.08	BDL	BDL	BDL	BDL	ND	BDL	BDL	ND	BDL	BDL	0.50	12.75	BDL	26.08
	May-2018	7.07	59.6	2.65	46.9	6.87	0.92	0.12	BDL	BDL	BDL	BDL	ND	BDL	BDL	BDL	BDL	BDL	0.30	4.15	BDL	24.91
GW-4	Oct-2017	6.92	65.4	2.98	85.5	18.9	2.00	0.26	BDL	BDL	BDL	BDL	ND	BDL	BDL	ND	BDL	BDL	0.64	20.16	2.48	55.76
	May-2018	7.18	133	3.15	63.6	8.67	0.72	0.14	BDL	BDL	BDL	BDL	ND	BDL	BDL	BDL	BDL	BDL	0.28	9.51	BDL	23.07
GW-5	Oct-2017	7.02	107	2.96	77.3	20.4	1.26	0.10	BDL	BDL	BDL	BDL	ND	BDL	BDL	ND	BDL	BDL	0.61	19.87	BDL	98.66
	May-2018	7.24	176	2.58	67.6	10.2	3.27	0.07	BDL	BDL	BDL	BDL	ND	BDL	BDL	BDL	BDL	BDL	BDL	24.82	BDL	59.63
DW-1	Oct-2017	7.30	159	2.86	75.6	14.1	0.28	0.11	BDL	BDL	BDL	BDL	ND	BDL	BDL	ND	BDL	BDL	0.55	22.29	BDL	49.39
	May-2018	7.26	183	2.74	75.7	11.4	0.06	0.07	BDL	BDL	BDL	BDL	ND	BDL	BDL	BDL	BDL	BDL	BDL	22.68	BDL	49.24
DW-2	Oct-2017	7.48	113	2.29	46.7	7.85	0.10	0.14	BDL	BDL	BDL	BDL	ND	BDL	BDL	ND	BDL	BDL	0.54	20.43	BDL	32.89
	May-2018	7.40	123	2.56	62.7	8.70	0.05	0.16	BDL	BDL	BDL	BDL	ND	BDL	BDL	BDL	BDL	BDL	0.24	8.51	BDL	35.48
CS	Oct-2017	8.11	93.0	4.20	59.7	15.4	0.47	0.16	BDL	BDL	BDL	BDL	ND	BDL	BDL	ND	BDL	BDL	0.59	14.06	BDL	53.36
	May-2018	8.29	91.2	3.34	73.0	13.5	0.01	0.06	BDL	BDL	BDL	BDL	ND	BDL	BDL	BDL	BDL	BDL	BDL	19.67	BDL	49.46
Lake	Oct-2017	9.16	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	May-2018	9.02	146	9.23	26.1	26.3	0.03	0.01	BDL	BDL	BDL	BDL	ND	BDL	BDL	BDL	BDL	BDL	BDL	27.54	BDL	83.99
SW	Oct-2017	7.04	61.3	2.91	103	16.7	0.25	0.09	BDL	BDL	BDL	BDL	ND	BDL	BDL	ND	BDL	BDL	0.48	16.46	4.11	91.88
	May-2018	7.10	78.3	3.35	85.0	13.3	BDL	0.06	BDL	BDL	BDL	BDL	ND	BDL	BDL	BDL	BDL	BDL	BDL	17.75	9.25	87.97

BDL indicates below detection limit (Cation: 0.01 mg/L; F: 1.1 mg/L; NO₃: 0.5 mg/L). ND indicates not detecting.

Table A8. PSD, soil texture, fractal dimension (D_m) of soil samples and reference values of D_m [49].

Sample	Particle Size Distribution (%)					Soil Texture	Fractal Dimension (D_m)
	Clay (<2 μm)	Silt (2–50 μm)	Fine Sand (50–250 μm)	Medium Sand (250–500 μm)	Coarse Sand (500–2000 μm)		
Potential value							2.555 (± 0.036)
Extreme value							2.298 (± 0.082)
S-1	2.16	44.33	43.67	4.95	4.90	Sandy loam	2.288 (± 0.040)
S-2	4.51	76.16	19.33	0.00	0.00	Silt loam	1.978 (± 0.054)
S-3	6.14	64.35	28.54	0.97	0.00	Silt loam	2.256 (± 0.045)
S-4	4.35	75.56	20.08	0.00	0.00	Silt loam	1.951 (± 0.053)
S-5	2.06	44.79	45.34	6.46	1.34	Sandy loam	2.156 (± 0.037)

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