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Vegetation recovery and groundwater pollution control of coal gangue field in a semi-arid area for a field application

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A B S T R A C T

This paper studied the impact of a gully-type gangue dump in the Daliuta mine area, Shaanxi, China on the groundwater environment and its contamination control. Multiple methods including eco-hydrogeological survey, soil column leaching test, field test and groundwater flow analysis were applied in the study. According to the field survey, the stack of gangue had changed the original feature of groundwater flow system, with the groundwater level of the gangue field raising about 1–3 m compared with the condition before the establishment of gangue dump. The long-term immersion of gangue had released various harmful substance into the groundwater and affected the downstream areas. The leaching test showed that the loess could significantly purify the mine wastewater by increasing pH value from 4.5 to 6.2–6.7 and absorbing heavy metals. Based on the loess column test, two loess permeable reactive barriers (LPRBs) were established in situ to improve the groundwater environment of gangue field. Besides, the vegetation restoration had been successfully carried out by covering a 30 cm-thick loess layer on the coal gangues and planting Alfalfa and Artemisica ordosica to improve the ecological environment, and the vegetation coverage had increased from 10% in 2008 to about 65% in 2013.

1. Introduction

The migration and transformation of pollutants in groundwater are affected by the water-rock interaction (Olaka et al., 2016), microbial action (Maizel et al., 2016; Cesar and Roš, 2013; Li et al., 2014; Da Silva and Corseuil, 2012; Souza et al., 2009), and human activities (Da Silva and Bonotto, 2015; Fabro et al., 2015) among others. The coal resource is rich in China and has been the main energy for a long time. However, coal mining can cause negative impacts on the regional environment. The change in coal mine geo-ecological environment is a result of human activities that destroy the system construction and function (Davis et al., 2010; Cherry et al., 2001; Moldovan et al., 2008; Sasamoto et al., 2004). There are three main impacts of coal mine development on the environment, including changing the groundwater flow system, disturbing the soil and causing ecological degradation. Coal mining produces large amounts of mine wastewater and gangue leachate, which can be acidic and contain high concentrations of sulfide and heavy metals (Gibert et al., 2011; Miao et al., 2012); the uncontrolled discharge of mine water could degrade the water quality of the receiving water body (Nordstrom, 2011). Ao and Huang (2005) found that the Wuda mining gangue dump of Inner Mongolia has been heavily polluted as evidenced by the lower pH value and high concentration of SO_4^{2-} in the surface water around the gangue dump. The coal mine wastewater and coal gangue leachate can discharge harmful heavy metals, radioactive elements, polycyclic aromatic hydrocarbons and other organic pollutants, which may cause hydrogeochemical reactions and consequently significant increase of TDS and hardness in groundwater, pollution of soil and deterioration of ecological environment (Sydnor and Redente, 2002; Gomo and Vermeulen, 2014; Khalil et al., 2013). High level of acidity and heavy metals in coal gangue field are regarded as key factors limiting plant growth and vegetation restoration (Chadwick, 1973). Currently, CaO or $CaCO_3$ are commonly used to regulate the pH of the mine water and soak solution of coal gangue, and appropriate plants are known to be able to stabilize or extract heavy metals in soils (Marseille et al., 2000). Therefore, how to

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remove heavy metals and select suitable species for ecological restoration has been one of the hot issues in ecological restoration research and practice in coal gangue fields.

This study analyzed the effect of the establishment of loess permeable reactive barriers (LPRB) and the pavement of a loess layer for vegetation recovery in the Daliuta mine area, Shaanxi, China. Multiple methods, such as eco-hydrogeological survey, laboratory and field experiments as well as groundwater pollution treatment were applied.

2. Materials and methods

2.1. Sites information

Daliuta coal mine is located on the north of Shaanxi province. This area is a transition zone of Maowusu sandland and loess hill, which belongs to Yanhe stratum of Erdos section of North China formation. The studied gangue field is surrounded by active, fixed and semi-fixed sand dunes and is located in a valley 4.8 km away from the Wulanmulun River in the east. The unconfined aquifer of this area consists of Quaternary residual sand, aeolian sand and lacustrine silty-fine sand (Fig. 1). The mean annual rainfall is 440.8 mm, 71% of which falls from June to September every year. The total evaporation is 2163 mm per year.

2.2. The investigation of the gangue field

The Gangue field is surrounded by 10–40 m high sand dunes. The Neogene mudstone aquiclude is under Quaternary aeolian sand. The gangue field has been stacked since April 2003. The field has been piled up with 2.5×10^6 m^3 gangue reaching the height of 20 m on average until February 2007. The characteristics of groundwater flow have been changed by the gangue dumps in the valley. The valley as the local discharge channel of unconfined water before the gangue being stacked, receives recharge in rainy seasons and phreatic water occasionally. Since waste rocks were piled, the evaporation receded greatly, and the discharge of groundwater into the valley from sides stored in pores of coal gangue. At the same time, precipitation was capable of recharging the aquifer quickly through the loose pores of the gangue pile. Therefore, the phreatic water level of the gangue field has risen 1–3 m after four-year stack according to the observation at probe holes in June 2008 (Fig. 2). The long-term soak of coal gangue at the bottom of the gangue pile produced a large number of leachate under water-rock interactions, and caused water pollution.

2.3. Water pollution survey

According to the hydrogeological setting surrounding the gangue field, two samples from surface water and four samples from groundwater in the study area were collected in March of 2008. Sample L2 and L3 were collected from the stream in the valley. Sample L1 was collected from the spring vent upstream the study area, sample L4 and L5 from the wells, while sample L6 from the soaking solution of the coal gangue (Fig. 3). The concentrations of Zn, Cu, Ni, Cr, Hg, Mn, As in water samples were measured using inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7500a, Santa Clara, CA, USA). The concentrations of NO_3^- and F^- were tested using DXO120 ion chromatography in the laboratory, as shown in Table 1.

2.4. Loess feature of coal mine area

Loess is widely distributed in Daliuta coal mine area. It is covered by silty sand (50%), clay (15–30%) and silver sand (30%). Quatz, one of the main mineral compositions of the loess accounts for more than 50%, followed by mica, amphibole and feldspar. SiO_2, the dominant chemical composition in loess accounts for more than 50%, followed by Al_2O_3, CaO, Fe_2O_3, MgO, K_2O, Na_2O, FeO, TiO_2, etc. The studied loess are characterized by small particles with large specific surface area, and a large amount of clay minerals with negative charges to absorb positive ions. Therefore, the loess strata have large adsorption capacity for heavy metal pollutants.

2.5. The loess column experiments of absorbing heavy metals

Considering the unavailability of massive soak solution of gangue and the similar chemical compositions of the gangue soak solution and coal mine wastewater, the wastewater from Daliuta coal mining was applied as the input solution of the loess column experiment. The loess was taken from the north hills of the coal mine. The grain size of experimental loess was 0.05–0.10 mm, the porosity was 0.32 and the volume weight was 1.54×10^3 kg/m^3.

The column experimental setup was an organic glass column with a diameter of 8 cm and length of 100 cm. The loess sample was air dried, sorted and then packed into the organic glass column high up to 70 cm with the nature density (Fig. 4). In order to avoid the disturbance of loess and blocking of the outlet, 1 cm-thick pebble layer were laid on both ends of the loess column when filling the column. Unpolluted groundwater from upstream of gangue field was injected into the loess column from the bottom for water saturation to record the pore volume (PV). After the loess was saturated, 3–5 PVs water was injected from the top of the loess column to wash way desorbed ions. At last, the coal mine wastewater was added into the loess column and kept at a certain level for the leaching test. Each PV leachate from the loess column was collected and numbered before filter. Soluble metals such as Cu, Mn, and Cr were measured using filtered and acidified samples also by inductively coupled plasma mass spectrometry.

2.6. Remediation projection

According to the previous experience and the local conditions of climate, soil texture and precipitation, artemisia ordosica and alfalfa were selected as the optimal vegetation for ecological recovery of the mine. Both of the species are indigenous species, which can survive easily, keep the characteristics of local species, and moreover prevent invasive species to reduce the risk of biodiversity decrease and extinction of local species as well as the other ecological disasters.

The first stage of the project of the coal gangue plant started in April 2003 and ended in February 2007 with the volume of gangue stacks as 2.5×10^6 m^3. Based on further exploitation of coal in 2010, the second stage of the project was set up in June of 2011 to pile up gangues along the downstream of the valley.

A 30 cm-thick loess layer was covered on the top of the gangue field after the first-stage project had ended in March, 2008. Artemisia ordosica were planted in drilling way in early April, based on 13.5–16.5 kg/ha. Three months later, 2-or-3-year artificial reproducted Alfalfa was planted in points strain method with the spacing of 0.6 m $\times$ 0.4 m. A LPRB was built on the tertiary mudstone downstream of the gangue field to purify the gangue leachate. The LPRB was about 5 m high, 1.5 m wide at the bottom and 0.5 m wide at the top. The same LPRB was built in the second-stage project in the downstream of the gangue field in June 2012 since the first LPRB and observation hole were covered by the coal gangues (Fig. 5).

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