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Hydrogeochemical signatures and evolution of groundwater impacted by the Bayan Obo tailing pond in northwest China

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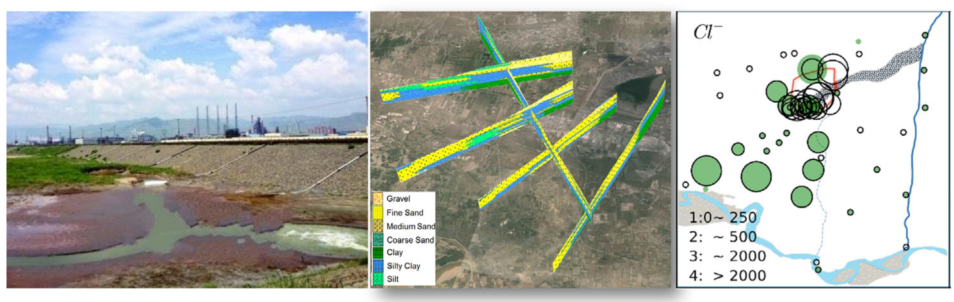
HIGHLIGHTS

- Combining hydrogeochemical methods and multivariate statistical analysis.
- First reporting geochemical processes in aquifers nearby Bayan Obo REE tailing pond.
- No geochemical evidence for uranium and thorium contamination in shallow groundwater.

GRAPHICAL ABSTRACT



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ABSTRACT

Uncontrolled leakage from mine tailing ponds can pose a serious environmental threat. Groundwater quality in a semi-arid region with extensive worries about the leakage from one of world's largest tailing ponds is studied herein through an integrated hydrogeochemical analysis and multivariate statistical analysis. Results show that elevated concentrations of NO_2^-, B, Mn, NH_4^+, F^-, and SO_4^{2-} in groundwater were probably caused by leakage from the tailing pond and transported with the regional groundwater flow towards downstream Yellow River. While NO_2^- contamination is only limited to areas close to the pond, high B concentrations persist within the contaminated plume originating from the tailing pond. Our current study shows that there is no geochemical evidence for U and Th contamination in groundwater due to leakage from the Bayan Obo tailing pond. Combining effects which includes regional variations, pond leaking and downstream mixing, mineral precipitation and dissolution, redox processes, ion exchange processes and agricultural activities, controlled groundwater hydrogeochemical signatures in the studied area. This study demonstrate that an increase in knowledge of evolution of groundwater quality by integrating field hydrochemical data and multivariate statistical analysis will help understand major water–rock interactions and provide a scientific basis for protection and rational utilization of groundwater resources in this and other tailing-impacted areas.

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1. Introduction

Mine tailings are often stored in pond behind dams, which often pose serious threat to surrounding environment because of potential dam failure, seepage of potential hazardous contaminants, negative visual impacts and damage of substrate bearing capacity (e.g., Johnson and Hallberg, 2005; Wolkersdorfer, 2008; Pan, 2010). Many tailing sites are historically adjacent to water bodies and immediately surrounded by industrial and agricultural areas (e.g., Penman, 2001; Olías et al., 2004; Pan, 2010). However, the impacts of these tailing ponds on nearby groundwater quality were not well studied or reported probably because of no routine monitoring and few complete hydrogeochemical data. There are not such many examples as mine sites in the Odiel River basin (e.g., Olías et al., 2004), the Old Rifle site and Hanford site (e.g., Zachara et al., 2013), where contaminated groundwater was studied in details. While significant efforts have been made to understand the behavior and fate of leachate plumes emanating from unlined tailing ponds or ponds with ruptured liners at their base as well as pit lakes (e.g., Johnson and Hallberg, 2005; Pan, 2010), groundwater quality impacted by above-ground tailing ponds has rarely been well documented. The high elevation of the above-ground tailing pond, which generates relatively high hydraulic gradient, causes its leaking events and the associated impacts on the groundwater system, which are not only limited to immediately downstream areas of the pond, but extended to farther areas.

A growing environmental awareness in China has led to increasing concerns for the risks from dam failures and waste disposal management associated with mining activities (e.g., Pan, 2010; Guo and Tong, 2011; Zhang, 2013). Based on data compiled in China in 2009, there were 26,000 registered tailing ponds while 300 new ponds were being constructed on average each year (Shen et al., 2011). So far, however, very few studies have comprehensively investigated the impacts of leakage of tailing ponds, identified characteristic hydrochemical changes in the surrounding aquifers and further determined whether groundwater quality has been deteriorated. The Bayan Obo (Baiyun Erbo or Baotou) tailing pond, known as the largest rare earth elements (REE) tailing pond in the world (e.g., Yu et al., 2012; Hurst, 2010; Huang et al., 2014), has received large volumes of tailings from the Baogang flotation-hydrometallurgical processing plant since the 1960s. The Baogang processing plant smelts ores which are extracted from the giant Bayan Obo deposit. At the earlier years of its operation, eco-environmental risks were not comprehensively examined and the pond was constructed as an "artificial lake" without full pre-cautions to protect the surrounding environment. More recently, however, with increasing pond levels in conjunction with rising environmental awareness, the Bayan Obo tailing pond has received an urgent-extensive call to comprehensively study and initiate remediation of the site, if deemed necessary (e.g., Xu et al., 2005; Guo and Tong, 2011; Huang, 2011). The major concerns are driven by the potential threat to the downgradient Yellow River, which is the primary water source for approx. 150 million people. Some sparse data regarding the surrounding hydrogeology were collected and reported by Shen and Liu (1957); Zhu (1962), and Fang (2006), and other limited groundwater quality data were reported by Zheng and Lu (1986) and Wang and Tu (1990). Also, recently Liao (2013) developed a regional flow model to investigate strategies for a sustainable development of groundwater resources in Baotou City, without considering hydraulic impacts from that tailing pond. The most comprehensive overview of previous activities was recently contributed by Huang et al. (2014), who summarized the sparse historical data with a systematic review on leachate and their background concentrations in groundwater. Their study suggested that uncaptured leakages had resulted in a plume of pervasively contaminants that extended in southwestward direction towards the downstream fluvio-lacustrine aquifer, and had probably reached the Yellow River alluvium plain and its contiguous swamps.

In this study, integrating existing and our new data, we use a range of techniques to elucidate what processes control the hydrogeochemical evolution of the groundwater system between the tailing ponds and the Yellow River. Principle component analysis (PCA) and Hierarchical cluster analysis (HCA) were used to constrain the relationships among groundwater constituents. The overall objective of this study is to identify whether, and if, to what degree leakage from the Bayan Obo tailing pond and other anthropogenic sources have contaminated the shallow aquifer system and the Yellow River, and what risks this may pose at present and in future. Therefore, this study will provide essential guidance for the future management of the groundwater systems and remediation requirements, while also guiding future monitoring activities.

2. Material and methods

2.1. Hydrogeological setting

The study area is located in the Yellow River alluvial plain near the piedmont of the Daqingshan Mountains, which also belongs to the western part of the Hubao plain in northwest China. The northern Daqingshan–Wulashan piedmont fault and southern Lana fault divide this region into the piedmont clinoplain and the Yellow River alluvial plain (Wang, 2006). The piedmont region of the Daqingshan–Wulashan Mountains is a groundwater recharge zone which is mainly composed of pre-Cambrian fractured metamorphic rock while the down gradient piedmont clinoplain and alluvial plain are mostly characterized by Quaternary unconsolidated sediments (Wang, 2006) that host rather transmissive, saturated aquifers. The Quaternary unconsolidated sediments consisting of coarse alluvial gravels and pebbles are extensively interlayered within three major alluvial–pluvial fans (Shen and liu, 1957), i.e., the Hademen ravine, Kundulun River and Dongdaben gully in the north (Fig. 1). In the northern piedmont clinoplain (average elevation of 1080 m), which is characterized by an average slope gradient of 8%, a formation of substantial fractions of clayey sand mixed with gravel forms a high-yielding aquifer. The southern Yellow River alluvial plain is relatively flat with an average elevation of 1010 m and a slope gradient ranging from 0.1 to 1.0%, associated with small hydraulic gradients. Representative hydrogeological cross-sections are shown in Fig. 2. They depict the major geological layers in the vicinity of the pond. The sequence shown in Fig. 2 also includes a thick impermeable unit of Pleistocene–Holocene muddy clays, which acts as a broadly distributed confining layer between the deep confined and the shallow unconfined aquifers (Zhu, 1962; Zheng and Lu, 1986; Fang, 2006). The thickness of the shallow aquifer is generally 25 - 35 m. In the upgradient of the southern Yellow River alluvial plain, the shallow aquifer is mainly composed of gravel and pebbles. In the downgradient areas contiguous to the Yellow River, there are massive interbeds of fluviolacustrine sediments in the shallow aquifer. These detrital sediments mainly consist of silt, clayey silt, silty sand and clay, which were generated from earlier swamps and wetlands (Zhu, 1962; Fang, 2006).

A temperate climate with East Asian continental monsoon predominates in this arid to semi-arid area. The long-term annual rainfall is in the range of 175 to 400 mm with 2100 to 2700 mm of evaporation and more than 75% of the rainfall occurs between May and September (Supporting information Fig. S1) (Fang, 2006). The groundwater levels in the shallow aquifer varied from 1.2 to 6.6 m below ground level in 2013 and were generally higher in July 2013 (wet season) than in November 2013 (dry season). The amplitude of the seasonal variations in the water table was found to range between 0.1 and 1.5 m. The hydraulic gradient varied by approximately 0.5% regionally, but close to the tailing pond, it is locally higher, especially near the leachate collection trench and near the Baolan railway dyke (Fig. 1). For example, several local groundwater mounding (or spring) zones/points have continuously been observed nearby the railway dyke and trench. In areas below and around the pond, both the magnitude and the