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Hydrogeochemical processes between surface and groundwaters on the northeastern Chinese Loess Plateau: Implications for water chemistry and environmental evolutions in semi-arid regions

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ABSTRACT

A large area of the continents is covered by loess that is subject to fast erosion, but detailed research is lacking about processes influencing the hydrogeochemistry in loess-covered regions. This study presents the first $\delta^{18}O$ and δD, and major ion contents of various waters (rain, rivers, lake, springs and wells) from Daihai Lake catchment on the Chinese Loess Plateau (CLP). In combination with historical hydrological and meteorological data during the past 60 years, we investigate factors affecting water chemistry and lake evolution on the CLP, and thereby provide insight into hydrogeochemical processes under semi-arid climatic conditions.

On the northeast CLP, river and groundwaters show elevated TDS (450 and 461 mg/L, respectively), about ~4 times higher than the global river mean value. Their water chemistry is dominantly influenced by carbonate weathering. Lake waters show even higher TDS at 5758 mg/L, ~50 times of the global mean, which is attributed to strong evaporation and associated with precipitation of calcite and dolomite. The order of carbonate (calcite and dolomite) saturation indexes follows lake water > river water > groundwater. Downstream rivers to the west of Daihai Lake are characterized by elevated SO_4^{2-}, indicating high lake levels in the past. Comparison of $\delta^{18}O$, δD, TDS and ion contents of river and groundwaters implies that shallow groundwaters are derived from surface runoff via fast infiltration, a hydrological process different from limited infiltration of groundwater on the Tibetan Plateau. Water quality assessment indicates that all river and 79% of well waters belong to moderately hard to hard-fresh waters, suitable for drinking and irrigation of plants with moderate salt tolerance. In contrast, all lake and spring waters and 21% of well waters belong to very bad water quality, and hence are not suitable for irrigation or drinking.

Owing to intensified human activities under drying and warming climate, the lake water level of Daihai declined by 4.83 m from 1955 to 2003, and started to accelerate since 1980. As a result, TDS and Cl^- increased by 1.8 times and Mg/Ca rose by 156 times from 1953 to 2010. Our data show that environment degradation poses a great threat to human occupation on the CLP. Considering the uniformity of loess, hydrogeochemical processes between surface and groundwaters on the loess regions may represent a widespread status of the CLP.

1. Introduction

Globally, about ~10% of land surface is covered by loess and loess-like deposits, and the portion increases to ~30% in China (Derbyshire, 2001; Liu, 1985). The Chinese Loess Plateau (CLP) covers an area of 640,000 km^2 with a thickness of >250 m, representing the largest and thickest loess regions in the world (Liu, 1985; Wang et al., 1984). Historically, the CLP has been a well-known political, economic and cultural center in China. The population on CLP increased from 10 million during the late Western Han Dynasty (2 A.D.) to 104 million by 2000 (Wang et al., 2006).

Due to the rapid population growth and unprecedented diffusion of human activities, water shortage has become one of the most prominent issues for the sustainable development of the CLP since the last century (He et al., 2003). The limited water resources are thought to greatly slow down the local economy growth. The climate on the CLP is mostly semi-arid, with low annual precipitation ranging from 150–300 mm in the north to 500–700 mm in the south (Li and Xiao, 1992). Sparse and deep groundwater resources result in harsh environments for plants, even in sub-humid regions in the south of the CLP (Zhang and An, 1994), and consequently most of agriculture relies on dryland farming (Li and Xiao, 1992). The Yellow River, as the world's fifth longest rivers, draining the CLP, has been experiencing frequent dry-ups since 1972, owing to increased irrigation, damming, and water diversion activities in the basin (Chen et al., 2003). The increasing

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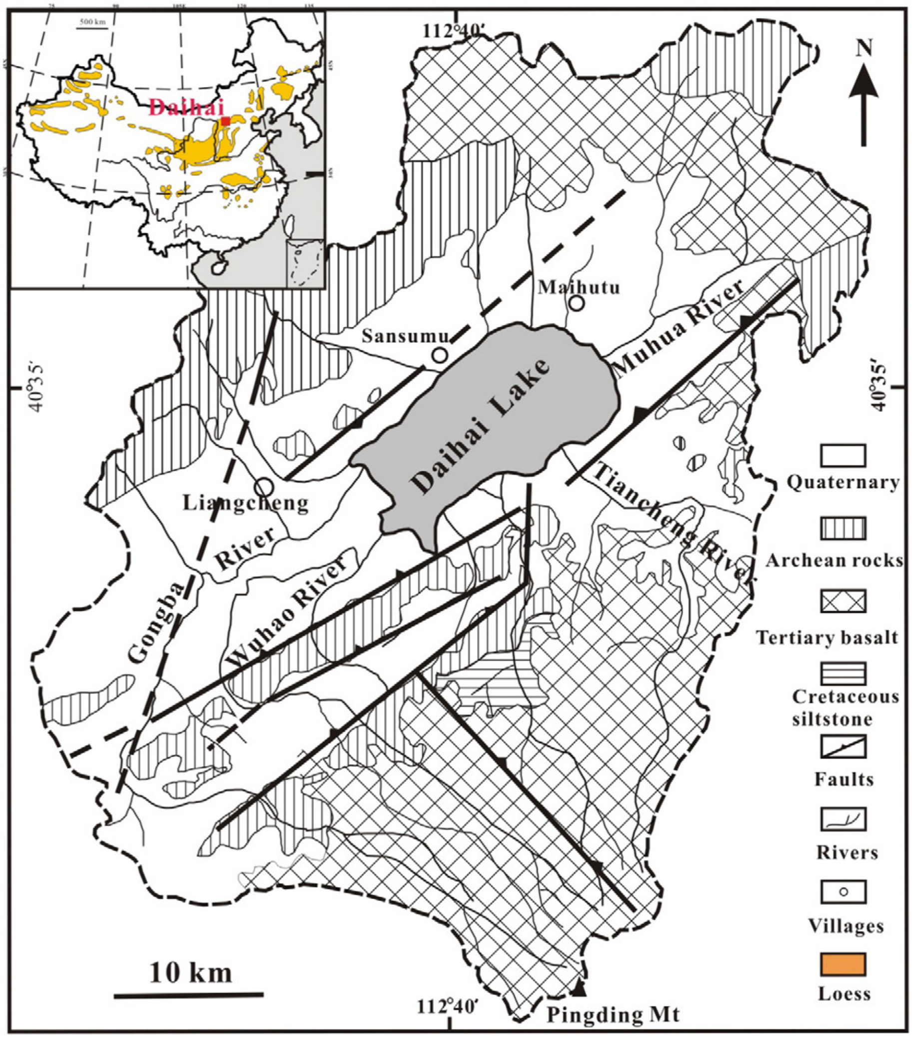

Fig. 1. Sketchy geologic map of the Daihai Lake catchment on the northeastern Loess Plateau. Inserted showing the location of Daihai Lake in China. Modified after Wang et al., 1990; Jin et al., 2006b.

number of flow stoppages has caused great economic and ecological losses. As an example, water supply could only fulfill 33.3% of the total need on the CLP in 2003 (Wang et al., 2006), and water shortage seriously affected the crop yield of dryland farming in the region (Wang et al., 2009; Zhang et al., 2009b). It has been suggested that, given optimum management of water and nutrients, agricultural production could be increased by as much as threefold (Fan and Zhang, 2000).

To date, in such huge regions, no systematical study exists on water chemistry, water cycle, and water quality assessment of surface and groundwaters on the CLP. Located at the northeastern of the CLP, Daihai Lake catchment has drawn great interests due to its potential for high-resolution paleoenvironment research (Jin et al., 2001, 2004, 2006a; Peng et al., 2005; Xiao et al., 2004). Its hydrologically-closed condition facilitates investigation of past hydrogeochemical processes in semi-arid regions. Here, we carried out a comprehensive study on geochemical and isotopic measurements of waters samples collected from Daihai Lake catchment. In combination with time-series records of water chemistry, hydrology, and human activities during the past 60 years, this paper aims to understand: (1) the water chemical characteristics and chemical weathering processes; (2) how natural and human factors affect the hydrology and water quality; and (3) key factors affecting lake evolution in the semi-arid region.

2. Study area

2.1. Geology

Daihai Lake is an asymmetric, east–west oriented graben-type basin, with steep north and gentle south. Outcropping bedrocks are predominantly Archean metamorphosed igneous rocks and Tertiary basalt with minor Cretaceous siltstones (Jin et al., 2006b). The Lake is mainly surrounded by Archean rocks. The lithology includes gneiss and granite (Wang et al., 1990). The Tertiary basalts are widely distributed in the southern mountain areas (Fig. 1) (Peng et al., 2005). Quaternary loess deposits are seen in the lake basin and river valleys, and overlying bedrocks (Fig. 2). The thickness of loess deposits varies from a few meters to more than ten meters (Jin et al., 2006b; Wang et al., 1990).

2.2. Geography and climate

Geographically, Daihai Lake (40°29′–40°37′N, 112°33′–112°46′E) is located in Inner Mongolia on the northeastern CLP. The catchment area is 2289 km^2. Four large and 18 small intermittent rivers drain into the lake. The four large rivers are the Gongba and Wuhao Rivers in the West, the Tiancheng River in the south, and the Muhua River in