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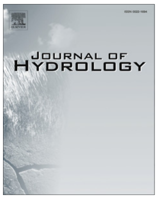

Identification of indicators of groundwater quality formation process using a zoning model

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SUMMARY

Drinking water safety is a world-wide focus. In Yinchuan Plain of western China, groundwater is mostly saline water, and it has generated many problems for the life of local residents. Yinchuan Plain exhibits differences from the mountain area to the plain in terrain and elevation, and landforms and scales. Such differences resulted in hydro-geological water storage structures with different water yield properties and permeabilities of the aquifers. These water storage structures are the places where the groundwater moves and is retained, as well as where the air–water–rock interaction and the migration and differentiation between substances in the water take place. With the arid climate and intense irrigation in Yinchuan Plain, the hydro-chemical features of the groundwater exhibit distinct zonation. To explore the formative mechanism of the groundwater quality in Yinchuan Plain, a zoning model for the formation of groundwater quality is established in three layers, the first layer shows the geological and hydrogeological conditions that express the landform and landscape, geological age, lithology, and hydrodynamic features of the studied area. The second layer indicates the zonation of the formation of groundwater quality. According to the major hydro-geochemical actions, the plain is divided from west to east into lixiviation, evaporation, and evaporation–mixing zones. The third layer contains the hydrodynamic features that express the hydro-chemical type, salinity, and the contents of the major ions as well as trace elements fluorine and arsenic. The features of each zone are quantitatively expressed with thermodynamic, hydrodynamic, and hydro-chemical indicators.

1. Introduction

Drinking water safety is a world-wide discussion focus. In arid and semi-arid regions, groundwater is the most important water resource and its quality is of the most concern. In the Yinchuan Plain in western China, benefiting from the Yellow River which runs through the plain, irrigation channels crisscrossed the whole plain and formed a so called "border-fortress oasis" that yields various crops, especially wheat. However, increasing human activities and the physical geographical conditions in this region resulted in complex chemical composition and high total dissolved solids (TDS) with 1–3 g/L in the shallow groundwater, and the contents of TDS, SO_4^{2-}, Cl^-, NO_3^-, NO_2^-, NH_4^+, F^-, total As, etc. in the groundwater have exceeded the national drinking water standards (Wan, 2005; Zheng and Wang, 2006; Zhang and Zhang, 2010). A portion of the local residents is facing problems with the saline water, by which their drinking water safety is threatened. Therefore, the formation of the groundwater quality in this region is a hot topic in the hydrogeology field.

Currently, studies on the formation of groundwater quality are mainly based on water–rock interaction, while focusing on four primary aspects, provenance, formative action, the theory of migration and differentiation, and quantitative simulation (Garrels and Thompson, 1962; Helgeson, 1968; Biqiyewa, 1981; Stumm and Morgan, 1981; Plummer et al., 1990; Cao and Hu, 1994; Wicks and Herman,1994; Cao et al., 2009; Howard and Mullings, 1996; Schofield and Jankowski, 2004; Murad et al., 2011). Many studies showed that the hydro-geochemical features of groundwater are important properties of groundwater systems. Spatially, hydro-geochemical features of groundwater often exhibit strong zonation (Troels,1957; Guo et al., 2005; Dragon and Jozef, 2009), which is mainly caused by the hydrogeological water storage structures from mountain area to plain with different scales and different water yield properties and permeabilities of the aquifers. These water storage structures are the places where

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the groundwater moves and is retained, and where the air–water–rock interaction and the migration and differentiation of substances in the water take place. Because of the differences in terrain and elevation, landform and scale, different water storage structures also, to a certain extent, have different hydrodynamics, substance migration intensities, and air–water–rock interaction strengths, leading to distinct zonation in hydro-chemical features (Cao et al., 2009). Commonly, groundwater is classified, according to its hydrogeological features, as bicarbonate water, sulfate water, chloride water, and transitional water between bicarbonate, sulfate, and chloride (Wei and Li, 1981; Sheng, 1986; Su and Wang, 2008; Dokuz et al., 2012). However, many factors would influence the chemical properties of groundwater during the formation of the groundwater chemical field; thereby, different zoning characteristics often appear in vertical or horizontal direction. In groundwater dynamics, groundwater is divided in vertical direction into upper intense alternation zone, middle slow alternation zone, and bottom extremely slow alternation zone (Biqiyewa, 1981). According to geochemistry and microorganism actions, aquifers are divided into high and low-iron content zones (Monjerezi et al., 2011). Based on geological environments, groundwater is divided into lixiviation, gathering, concentration, restoring, and added intense human-activities zones (Wang et al., 2004a). By groundwater dynamic field and hydro-geochemical actions, groundwater can be divided, in vertical direction, into atmospheric water infiltration diluting zone, near-surface evaporation zone, mudstone compaction drainage diluting zone i.e., pressure filtering concentration zone, clay mineral dehydration diluting zone, and leaching concentration zone. And in horizontal direction, it can be divided into atmospheric water infiltration diluting zone, mudstone compaction drainage diluting zone in the center of basins, transitional zone in leakage area, and concentration zone in leakage–evaporation area (Lou et al., 2006). These zoning methodologies are mainly qualitative descriptions of groundwater.

A variety of groundwater hydrochemical model and transport models including equilibrium speciation model (Morel and Morgan, 1972; Truesdell and Jones, 1974; Kharaka and Barnes, 1973), equilibrium mass transfer (Sposito and Mattigod, 1980; Wolery, 1983; Arnorsson et al., 1982), mass transport model (Miller and Benson, 1983; Pruess, 1991,1995) exist for quantitative description of hydrochemical evolution and mass transfer in a regional aquifer. These studies have led to a better understanding of the hydro-chemistical formation and evolution of arid basin systems. With hydrogeological unit entities as objects, Cao et al. (2009) studied the chemical indicators, and the values and distribution of carbon dioxide partial pressure of each hydro-geochemistry and hydrogeological zone from the recharge area to the bury area. In addition, for each entity, they identified the qualitative and semi-quantitative aquifer water yield properties and permeability, mineral saturation indexes, mineral dissolution and deposition of the zones, as well as the chemical indicators like the theoretical calcite dissolution and deposition rate, TDS, and hydro-chemical water types. Their study provided new ideas for the quantitative studies on hydro-chemical zonation.

In this study, a zoning model and the quantitative indicators were established to investigate the formation and evolution of groundwater quality based on the climate and geological conditions, human activities, and spatial distribution characteristic of the hydro-chemical composition of the studied area.

2. Materials and methods

2.1. Description of study area

Yinchuan Plain spans across 105°45′–106°56′E, 37°46′–39°23′N as Fig. 1 presents. Located at the upper reaches of the Yellow River, and higher in the west and lower in the east, the plain stretches from Qingtong Gorge to Shizui Mountain in south–north direction, and from Helan Mountain to the west edge of the Ordos plateau in west–east direction, with a total area of 7790 km^2. Helan Mountain in the west is a lithoidal submountain, with an overall slope of north–east 30°. In the east area, Taolingyan plateau has a wavy terrain, where in the higher areas traces of quaternary conglomerate residues can be found, and in the lower areas, diluvial and aeolian sand gravel, silty-fine sand, and loessial clay sand can be found. In the middle of the studied area is vast plain consists of piedmont alluvial plain, alluvial–proluvial plain, and alluvial lacustrine plain (including the second terrace and the first terrace) (as shown in Fig. 2), and this area tilts from the southwest to the northeast. The plain enjoys temperate inland arid climate, with annual average temperate of 8.92 °C, average annual precipitation of 186.7 mm, and average evaporation of 1838.44 mm (Ningxia Geological Engineering Survey Institute, 1995; Wan, 2005; Zheng and Wang, 2006; Jing et al., 2010). The main stream of the Yellow River, which is the primary river runs through the Yinchuan Plain, enters the plain at the southeastern end, crosses the entire plain along the east, and leaves from the first ridge of Shizui Mountain in the north (Fig. 1).

The aquifer of the studied area contains mainly pore water of quaternary loose rock, and consists of mainly fine sand, silty-fine sand, small amount of medium sand and clayey soil. The aquifer has a general buried depth of less than 5 m (Ningxia Geological Engineering Survey Institute, 1995; Zhang and Wang, 2003; Wan, 2005; Zhang and Zhang, 2010) and the flow direction of southeast to northwest, as shown in Fig. 2. Groundwater runoff in different areas varies in directions and conditions. In the piedmont alluvial plain area, the hydraulic gradient is greater than 10‰, which means the runoff is in larger rate, while in the alluvial–proluvial plain and fluvial lacustrine plain areas, the hydraulic gradient is only 0.5‰, thus the runoff is in smaller rate (Ningxia Geological Engineering Survey Institute, 1995; Zhang and Wang, 2003). The groundwater recharge sources are mainly the leakage of the Yellow River diversion canals, and infiltration of irrigation; the recharge amount from these sources accounts for more than 80% of the total groundwater recharge. The groundwater discharge mainly includes evaporation and drainage ditches, and these two kinds of discharge account for 45% of the total discharge (Ningxia Geological Engineering Survey Institute, 1995; Wang and Yu, 2001; Zhang and Wang, 2003; Wang et al., 2004a; Xue et al., 2006). Artificial exploitation has also become an important discharge channel along with the agricultural development and population increase in the area.

2.2. The method of a zoning model establishment

Different hydrogeological water storage structures with different water yield properties and permeabilities of the aquifer from mountain areas to plains are places where the groundwater moves and is retained, as well as where the air–water–rock interaction and migration and differentiation between substances in the water take place. Because of the differences in terrain and elevation, landform and scale, different water storage structures also to a certain extent have different groundwater hydrodynamics, substance migration intensities, and air–water–rock interaction strengths, leading to distinct zonation in hydro-chemical features. Therefore, a zoning model may been established to reveal the formative mechanisms of the groundwater quality as three layers by typical cross-section (Fig. 3). The first layer shows the geological and hydrogeological conditions. The second layer indicates the zonation of the formation of groundwater quality. The third layer contains the hydro-chemical features. Finally the three layers were mapped by using Mapgis software with a ratio of 1:250,000.