Journal of Hydrology 527 (2015) 433–441

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Hydrogeochemical characterization of groundwater flow systems in the discharge area of a river basin

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ARTICLE INFO

Article history:
Received 13 February 2015
Received in revised form 23 April 2015
Accepted 27 April 2015
Available online 5 May 2015
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Barbara Mahler, Associate Editor

Keywords:
Groundwater flow system
Hierarchal cluster analysis
Hydrochemistry
Isotopes
Water–rock interaction
Ordos basin

SUMMARY

The lowest reaches of a large-scale basin could be the discharge area of local, intermediate and regional groundwater flow systems with different travel distances and travel times. However, little research has been devoted to identify the flow systems in such a site. In this study, 44 groundwater samples were collected from wells with different depths in the discharge area of the Dosit River Watershed in the Ordos Cretaceous Basin. Using the major ions and pH as the input, hierarchical cluster analysis was conducted, which leads to five clusters (from C1 to C5) with distinct geochemical compositions. The relationship between δD and δ^{18}O shows that clusters C1 and C2 were recharged during the cold time while clusters C3, C4 and C5 were recharged recently. According to the Gibbs scheme, groundwater samples in all clusters except for C5 were controlled by rock–water interaction. Both hydraulic and geochemical perspectives were considered to identify the mechanisms of groundwater evolution. Both hydrochemistry and isotopes versus depth show a three-part structure with boundaries around depths of 200 m and 600–750 m, which were assumed to be associated with the circulation depths of local and intermediate flow systems. After excluding C4 with highly variable water-types, three geochemical indicators (Cl^-, SO_4^{2-}, and the slope of $(Ca^{2+} + Mg^{2+}) - (SO_4^{2-} + HCO_3^-)$ versus $(Na^+ - Cl^-)$ imply that the processes of water–rock interaction for clusters C1, C2 and C3 include dissolution of halite and gypsum, weathering of feldspar, and ion-exchange. Moreover, it was found that C3 from local flow system, C1 from intermediate flow system, and C2 from regional flow system has increasingly higher concentrations of Cl^- and lower values of Chloro-Alkaline index, which indicate increasingly higher degrees of dissolution and ion-exchange. This study not only reveals the mechanisms of groundwater evolution in the study area, but also provides a method to identify nested flow systems using hydrochemistry and isotopes.

1. Introduction

Groundwater circulation, which is an important component of the hydrological cycle, is extremely complicated in a large-scale groundwater basin. Tóth (1963) found that basin-scale groundwater circulation has a hierarchically nested structure, i.e., local, intermediate, and regional flow systems could develop. Each flow system has its own recharge area, discharge area and circulation depth. The hierarchically nested flow systems have been found to be related to many geological, chemical and biological processes (Batelaan et al., 2003; Cardenas, 2007; Gleeson and Manning, 2008; Marchetti and Carrillo-Rivera, 2014; Tóth, 1999) because of the interaction between groundwater and its ambient environment.

The geochemical composition of groundwater is mainly controlled by such processes as weathering, dissolution, ion exchange, and evaporation (Appelo and Postma, 2005; Deming, 2002; Freeze and Cherry, 1979; Hiscock and Bense, 2014). Therefore, lithology and climate generally determine the water type. Even if lithology is similar, the travel distance and travel time determine the degree of water–rock interaction, thus the geochemical composition. Therefore, hydrochemistry provides an excellent indicator to identify the sources of groundwater from different aquifers (Adomako et al., 2011; Barth, 2000; Cloutier et al., 2008; Currell et al., 2010; Demlie et al., 2007; Edmunds et al., 1982; Elliot et al., 1999; Fagundo-Castillo et al., 2008; Han et al., 2010; Kimblin, 1995; Montcoudiol et al., 2014; Portugal et al., 2005; Zhu et al., 2007) or the flow path from a recharge area to its corresponding discharge area (Adomako et al., 2011; Aji et al., 2008; Alconada-Magliano et al., 2011; Cartwright et al., 2004; Chen et al., 2004; Edmunds et al., 2006; Han et al., 2009; Herczeg et al., 1991; Mahlknecht et al., 2006; Montcoudiol et al., 2014).

According to Tóth's (1963) classic model, the lower reaches of a groundwater basin could be the discharge area of local,

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http://dx.doi.org/10.1016/j.jhydrol.2015.04.063
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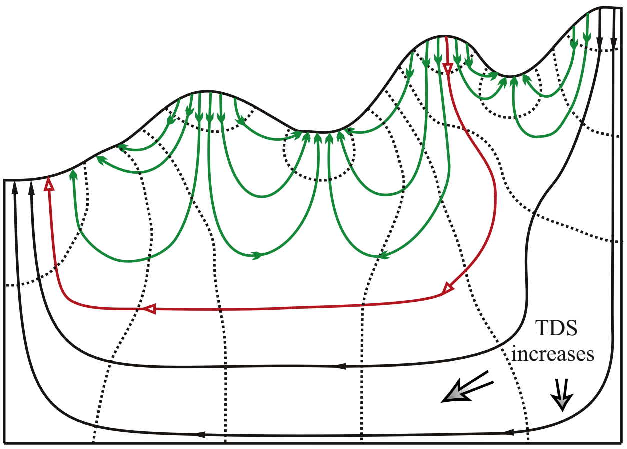

Fig. 1. A schematic figure showing the development of local, intermediate and regional flow systems (modified from Tóth, 1999). The green, red and black lines with arrows represent local, intermediate and regional flow systems. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

intermediate and regional flow systems (Fig. 1). In the Dosit River Watershed of the Ordos Cretaceous Basin, Northwestern China, there are numerous wells tapping the Cretaceous aquifer near the Dosit River. The numerous wells with different depths provide an excellent opportunity to sample groundwater from different parts of the aquifer in the discharge area of the watershed.

In this study, the hydrochemistry of groundwater from wells with different depths in the discharge area are examined, and the depth-dependent characteristics of hydrochemistry are related to the different groundwater flow systems, which have different travel times, travel distances and circulation depths.

2. The study area

The Dosit River Watershed is a sub-basin of the Ordos Basin in Northwestern China. Its longitude is from 106°54′28″ to 108°16′16″E and its latitude is from 38°18′21″ to 39°36′06″N, occupying an area of 10,924 km^2 (Fig. 2). The elevation of the Dosit River Watershed decreases from 1300 to 1400 m above the sea level in the east to 1000–1100 m in the west. The watershed has a semi-arid to arid climate. The precipitation decreases from 340 mm/year in the southeast to 220 mm/year in the northwest, while the potential evaporation increases from 2400 mm/year in the southeast to 2700 mm/year in the northwest (Jiang et al., 2014; Yin et al., 2011).

The main aquifer of the watershed is the poorly consolidated Cretaceous sandstone with a thickness of 700–1000 m, which is overlain locally by Tertiary mudstones and extensively by thin unconsolidated Quaternary sediments. The Jurassic mudstone with coal mines, which underlies the Cretaceous sandstone, is generally assumed to be an aquiclude. The Cretaceous sandstone and the Quaternary sediments constitute the main aquifer system, which is a thick unconfined aquifer. Quartz, albite and feldspars are the main minerals in the Cretaceous sandstone, while gypsum, halite,

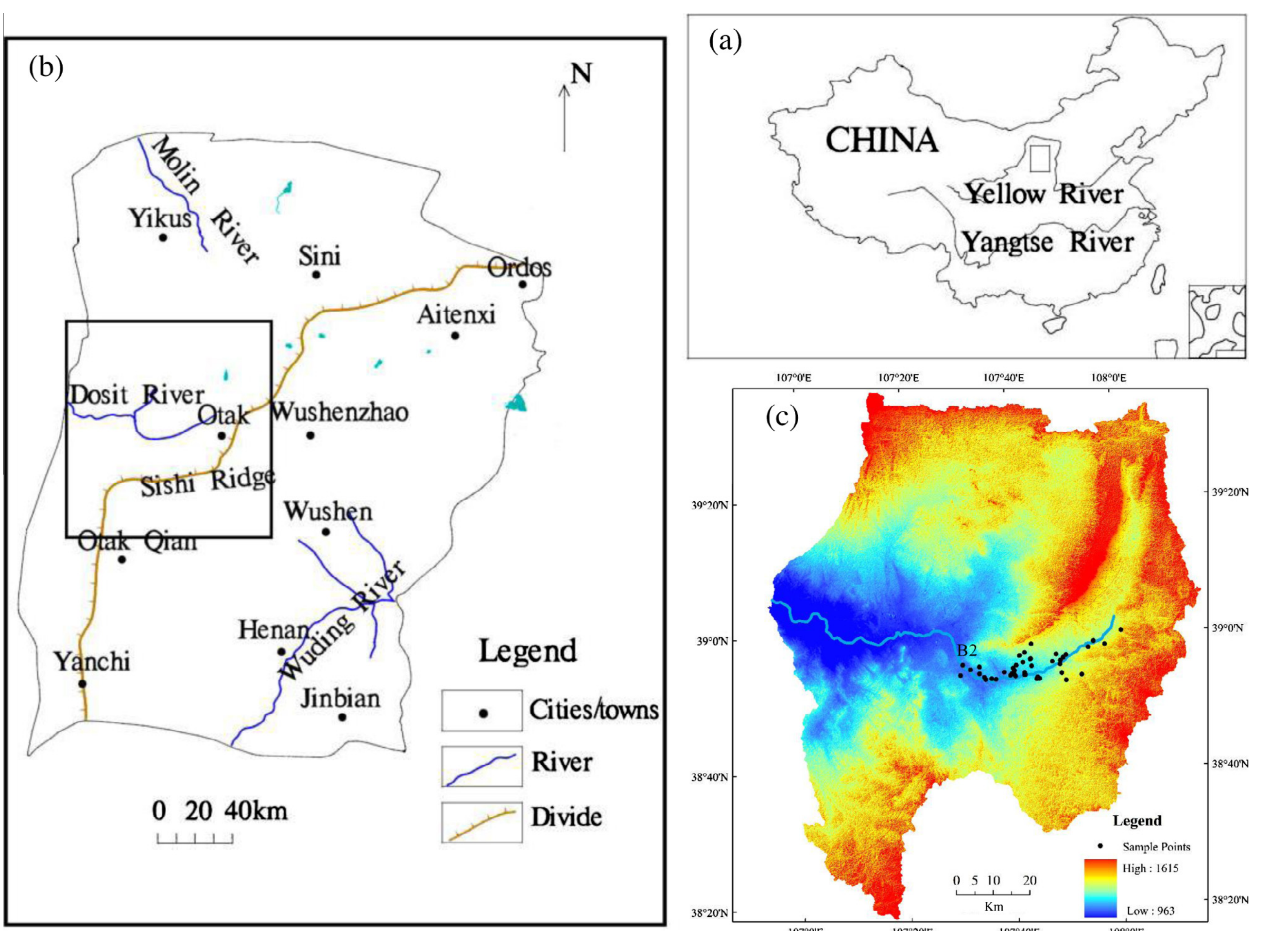

Fig. 2. (a) The location of the Ordos plateau; (b) the location of the Dosit River Watershed in the Ordos plateau; and (c) the topography and groundwater sample points in the Dosit River Watershed.