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Revised conceptualization of the North China Basin groundwater flow system: Groundwater age, heat and flow simulations

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ABSTRACT

Groundwater flow in deep sedimentary basins results from complex evolution processes on geological timescales. Groundwater flow systems conceptualized according to topography and/or groundwater table configuration generally assume a near-equilibrium state with the modern landscape. However, the time to reach such a steady state, and more generally the timescales of groundwater flow system evolution are key considerations for large sedimentary basins. This is true in the North China Basin (NCB), which has been studied for many years due to its importance as a groundwater supply. Despite many years of study, there remain contradictions between the generally accepted conceptual model of regional flow, and environmental tracer data. We seek to reconcile these contractions by conducting simulations of groundwater flow, age and heat transport in a three dimensional model, using an alternative conceptual model, based on geological, thermal, isotope and historical data. We infer flow patterns under modern hydraulic conditions using this new model and present the theoretical maximum groundwater ages under such a flow regime. The model results show that in contrast to previously accepted conceptualizations, most groundwater is discharged in the vicinity of the break-in-slope of topography at the boundary between the piedmont and central plain. Groundwater discharge to the ocean is in contrast small, and in general there are low rates of active flow in the eastern parts of the basin below the central and coastal plain. This conceptualization is more compatible with geochemical and geothermal data than the previous model. Simulated maximum groundwater ages of ~1 Myrs below the central and coastal plain indicate that residual groundwater may be retained in the deep parts of the basin since being recharged during the last glacial period or earlier. The groundwater flow system has therefore probably not reached a new equilibrium state with modern-day hydraulic conditions. The previous hypothesis that regional groundwater flow from the piedmont groundwater recharge zone predominantly discharges at the coastline may therefore be false. A more reliable alternative might be to conceptualize deep groundwater below the coastal plains a hydrodynamically stagnant zone, responding gradually to landscape and hydrological change on geologic timescales. This study brings a new and original understanding of the groundwater flow system in an important regional basin, in the context of its geometry and evolution over geological timescales. There are important implications for the sustainability of the ongoing high rates of groundwater extraction in the NCB.

1. Introduction

1.1. Regional groundwater flow in sedimentary basins

The gravity driven multiple-scale groundwater flow systems theory derived by Tóth (1963) is widely regarded as the paradigm for the modern study of regional groundwater flow (e.g., Lazear,

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2006; Cardenas, 2007; Gleeson and Manning, 2008; Schaller and Fan, 2009). Topography and groundwater table configurations determine the regional groundwater flow pattern, and therefore greatly affect the migration of solutes and convective heat transfer (e.g., Banner et al., 1989; Deming et al., 1992; Garven, 1995; Tóth, 1999). Many previous studies have examined how the topography/recharge controlled groundwater table configurations affect multiple-scale flow patterns (e.g., Haitjema and Mitchell-Bruker, 2005; Gleeson and Manning, 2008). Generally speaking, the combined effects of hydraulic characteristics (e.g., hydraulic conductivity), recharge rates, the geometric dimensions of the aquifer, and the relative positions of the recharge and discharge zones determine the dominant flow pattern. Using topography solely may lead to misunderstanding of groundwater flow system dynamics and thus problematic conceptualizations. It is therefore necessary to integrate information with respect to all of the controlling factors—including heterogeneous aquifer properties (e.g., Freeze and Witherspoon, 1967), influence of geological structure, and changes in boundary conditions due to geological and geomorphological evolution (e.g., Lemieux et al., 2008)—to more realistically evaluate the groundwater flow regime.

Groundwater flow regimes in regional systems result due to long-term transient responses to climate change and/or tectonic movements (Tóth, 2009; Schwartz et al., 2010). As aquifer pressure transfer is generally much faster than actual groundwater flow, the reliability of the premise of quasi-steady state under a specific hydraulic condition should be evaluated in a given timescale relevant to the size of the basin, considering the impact of past sea-level, climatic and tectonic evolution (Garven, 1995). In the absence of information allowing transient simulation of the flow system on geological time scales, groundwater residence time indicators in the aquifer can be used to constrain the time scales relevant to the groundwater currently existing in the aquifer, and help to understand the evolution of the system (e.g., Morrissey et al., 2010). Combining such information with groundwater age simulations may prove a powerful new approach to explore the dynamics and evolution of regional groundwater flow systems over geological timescales (e.g., Lemieux et al., 2008; Gupta et al., 2015). Groundwater age (or residence time) is the average time elapsed since recharge of the range of water molecules present in a sample, integrating the effects of advection, hydrodynamic dispersion and mixing (Goode, 1996; Bethke and Johnson, 2002; Massoudieh et al., 2012). Under flat topography in coastal plain areas, groundwater flow will be dominated by downdip horizontal flow along the axis of the aquifers, and ground water age generally show an increasing trend toward coast (e.g., Kennedy and Genereux, 2007; Schaller and Fan, 2009; Plummer et al., 2012; Stewart, 2012).

1.2. Previous conceptual model of regional groundwater flow in the North China Basin

The North China Basin (NCB) (also called Bohai Bay Basin), which includes the North China Plain (NCP) and the Bohai Bay, was developed on Archeozoic metamorphic basement. The NCP is the largest plain in east Asia, occupying an area of 140,000 km^2 in northeast China. It consists of numerous alluvial fans and alluvial plains extending from the Taihang Mountains on the west and Yanshan Mountains on the north, to the Bohai Bay in the east (Foster et al., 2004) (Fig. 1a). Several distinct phases of rifting and subsidence since Mesozoic and Cenozoic era resulted in a series of uplifts and depressions primarily trending to the northeast, creating a low-high-low tectonic framework (Ye et al., 1985) (Fig. 1b). The basin consists of a series of Paleozoic, Mesozoic, and Cenozoic sediments; and the continuous deposition process since the Neogene period resulted in as much as 2500 m of Neogene and Quaternary sediments covering the older basement (Fig. 2). Migration of oil and transfer of heat have been shown to be strongly related with groundwater flow in the basin (Chen, 1988). A reasonable and reliable conceptual model for groundwater flow in the basin is important for sustainable usage of groundwater (including thermal water) as well as oil, gas and salt/brine.

Conceptualization of the groundwater flow system built on previous studies is based on two primary premises: (1) the Neogene deposits act as a low-permeability aquitard below the Quaternary aquifers; (2) groundwater in the Quaternary aquifers is in a quasi-equilibrium state with the modern landscape and hydraulic conditions. Under these hypotheses, the groundwater flow patterns were inferred based on topographic relief and water table configurations (see Fig. 1a); and a regional groundwater flow system was proposed extending throughout the Quaternary sediments (Fig. 3) in the basin, traveling a distance of ~300 km from the mountainous areas in the west and north to the Bohai Bay in the east (Fig. 4) (Zhang and Payne, 1987; Zhang et al., 2000; Chen et al., 2005). However, this conceptualization of the groundwater flow regime was assumed without a systematic analysis of recharge/discharge distribution, hydraulic continuity (between different provinces of the basin) and assessment of the timescales of flow. Groundwater flow patterns are highly related with the depth of the basin, with deep basins theoretically generating a greater vertical component of flow under the same flow-inducing forces (Tóth, 1963; Freeze and Witherspoon, 1967). In the NCB, the ratio of thickness of the Quaternary aquifer to the width of the generally inferred regional flow system is about 1/500, suggesting a very shallow basin with limited potential to generate vertical components of flow and thus local discharge points across the basin. However, the underlying impermeable Pre-Cambrian basement reaches a depth of up to 10 km (Yang and Xu, 2004), and there is a substantial thickness of Neogene sediments underlying the Quaternary aquifers which may be important in the flow system. After decades of hydrogeological investigations and data collection in the NCB, the hydrological and in particular geochemical datasets (e.g., radio-isotope tracers) have been shown to conflict with the inferred flow regime of this conceptual model (see Section 2.3). As a reliable conceptual model is crucial for groundwater development (e.g., Gillespie et al., 2012), this makes it necessary to re-assess and revise the previously constructed groundwater conceptual model and explore alternative hypotheses.

1.3. Aims of this study

As the hypothesis of the regional horizontal groundwater flow regime under modern hydraulic conditions has failed to explain the regional stable and radiogenic isotope data, the originally developed conceptual model of groundwater flow in the NCB needs to be re-examined, integrating information on the basin geometry, aquifer heterogeneity and climatic/geomorphological/geological evolution. The primary objectives of this study are:

1. Evaluate the impact of different combinations of hydraulic parameters and boundary conditions on groundwater flux, flowpaths, groundwater age distributions and heat transport in the NCB.
2. Use coupled groundwater flow and solute transport modeling to estimate theoretical maximum groundwater ages under modern hydraulic conditions, thus constraining the timescale required for the basin to reach a 'quasi-steady state' with prevailing landscape and hydrological/climate conditions.