Numerical simulation of groundwater age distributions in the hierarchical subsurface flow system: a case study of Jinan in northern China

J L Wang¹,4, M G Jin², Z G Wang¹ and B J Jia³
¹Department of Soil and Water Conservation, Changjiang River Scientific Research Institute of Changjiang Water Resources Commission, Wuhan, China
²School of Environmental Studies, China University of Geosciences, Wuhan, China
³Wuhan CTI-CRSRI Engineering & Environment Co., Ltd., Wuhan, China
E-mail: jialewang1989@126.com

Abstract. Understanding groundwater age is essential for the aquifer management. In this study, a typical hydrogeological cross section in Jinan is selected to set up a coupled groundwater flow and age transport model. The simulation results show that hierarchical groundwater flow systems, composed by the nested local, intermediate and regional subsystems, are developed from the northern piedmont of Mount Taishan to Qiguang Fault. The scales of these flow subsystems are primarily controlled by the topography. Aquifer lithology variations also influence the groundwater flow system. Groundwater age distributions are closely related to the flow system. Groundwater age becomes older along the flow paths and increases abruptly near the internal stagnation point, which can be used as a characteristic boundary between different groundwater flow hierarchies. The results of the present research will not only help understand the groundwater circulation regimes in Jinan, promote the rational development and utilization of groundwater resources, but also provide references for the practical applications of groundwater flow system theory.

1. Introduction

The age of groundwater, as an intrinsic property, bears important information on groundwater circulation and evolution. Thus understanding groundwater age is essential for water resources management. Evaluation of groundwater age is the key for the assessment of aquifer renewability, replenishment, and vulnerability, and also supports identification of groundwater flow paths, estimation of aquifer properties and groundwater velocities, as well as recharge rates [1-3].

Two approaches are usually used to estimate groundwater ages: (i) measuring natural or man-made tracers in groundwater and (ii) modeling of groundwater ages by mathematically solving the transport equation. When using environmental tracers to evaluate age distributions in groundwater system, the complexity of groundwater transport processes are often considerably reduced. The environmental tracers used for groundwater age dating, as well as their applications and defects have been reviewed by Phillips and Castro, Kazemi et al and etc [4,5].

The groundwater age modeling methods are generally classified into three approaches, namely the advective model, the solute transport model, and the age mass transport model [6]. By comparing the simulated age distributions in the Carrizo aquifer through those three different modeling approaches, it
is found that when mixing processes are non-negligible and groundwater velocities vary severely, the most consistent age distribution can be acquired through the age mass transport approach [7]. Thus, the age mass transport method should be the preferred approach to calculate groundwater age distributions in the hierarchical subsurface flow system, where flow velocities exhibit strong variation [6].

The present study was conducted in Jinan, a typical spring catchment in northern China. 108 springs are distributed in the urban area. With the development of the local economy, groundwater exploitation is continuously increasing but lacks scientific and reasonable planning and regulation. As a consequence, many springs in Jinan are facing flow attenuation or even drying up. Therefore, a comprehensive understanding of the groundwater flow system in this area is in urgent need.

Previous studies in Jinan were primarily concerned with the geological structure, groundwater table and spring outflow dynamics [8,9]. Wang et al conceptualized the groundwater flow system of Jinan into a hierarchy of local, intermediate and regional subsystems, based on the hydrological and chemical information from groundwater discharge areas [10]. However, few, if any, quantitative researches are conducted on the subsurface flow system in Jinan, which is necessary for the accurate management and protection of groundwater resources.

In this paper, the hierarchical groundwater flow system in Jinan is taken as a field case study. A coupled subsurface flow and age transport model is employed to quantitatively analyse different groundwater flow hierarchies and age distributions.

2. Geological setting

Jinan is located in a monoclinic geological structure, with topographical elevation gradually declining from south to north. Land view transits successively from mountain terrain in the south, to the piedmont plain, and finally to the alluvial plain in the north (figures 1 and 2).

Metamorphic rocks (Art), exposed in the south, constitute the basement of the aquifer system in Jinan. Limestone and shale are interbedded in the Cambrian strata, overlaying the Art basement. The overlying Ordovician, composed by the thick layers of limestone, constitutes the most productive aquifer in Jinan. Mesozoic igneous rocks, composed by diorite and gabbro, exist in the northern Jinan city and are mostly covered by Quaternary deposits.

![Figure 1. Geological setting of the study area. A–A’ refers to the cross section shown in figure 2 (modified after [10]).](image-url)
Karst groundwater generally flows from south to north, coinciding with the regional topography and dip direction of karst strata. Karst groundwater mainly discharges in the form of ascending springs in Jinan city as blocked by the igneous rocks. Regional groundwater continues to move northward with deeper circulation depth and longer flow path. The overlying Carboniferous, Permian, Triassic and Neogene constitute the relative aquicludes in the system.

The cross section A-A’ (figure 2) stretches from the divide of Mount Taishan in the south to Qiguang Fault in the north, covering all the landforms and topographical features in the study area. This cross-section is parallel to the regional groundwater flow direction, and goes through all the aquifer groups in Jinan. Therefore A-A’ is a typical cross section in studying the Jinan groundwater flow system. In this paper, a two-dimensional numerical model is constructed based on the profile A-A’.

3. Mathematical models

The two-dimensional steady flow assumption has been commonly applied to regional scale subsurface flow and transport model [11,12]. It is often supposed that the groundwater age distribution is constant over many years. So the groundwater flow equation under steady state is used in the present study to calculate the subsurface flow field:

\[ \nabla \cdot (K \nabla h) = 0 \]  

(1)

where \( K \) is the hydraulic conductivity tensor, \( h \) is the hydraulic head.

In this paper, the age mass transport approach is employed to evaluate groundwater age distribution, given its advantages over other two age modeling methods. The equation for the age mass transport under steady state is [13]:

\[ \nabla \cdot (\theta D \nabla \tau) - \nabla \cdot (\mathbf{u} \theta \tau) + \theta = 0 \]  

(2)

where \( \tau \) is the groundwater age, \( \theta \) is the effective porosity, \( \mathbf{u} \) is the pore-water velocity vector, \( D \) is the dispersion coefficient tensor.

The two-dimensional coupled groundwater flow and age mass transport equations under steady state are solved numerically through finite element calculation via FEFLOW software (version 6.2, DHI-WASY).

4. Numerical model

The profile A-A’ (figure 2) comprises all types of aquifer groups in the study area, including: (1) porous aquifers composed by Quaternary sediments (Q), (2) fissure karst aquifers composed by Ordovician carbonate rocks (O), (3) karstic fissure aquifers composed by Cambrian clastic rocks with interbeds of carbonate rocks (Є), (4) fissure aquifers composed by the metamorphic rocks of Archean Taishan Group (Art). Gabbro (γ) as well as Carboniferous (C), Permian (P), Triassic (T), Jurassic (J), Neogene (N), which are mainly composed by sandstone, mudstone and shale with relatively low permeability, are divided into aquicludes. Based on the hydraulic properties of each strata in the profile A-A’, the model structure can be generalized as shown in the figure 3 with the length of 88 km.
and altitude difference of approximately 3400 m.

The model domain is bordered by the average phreatic surface on the top, the divide of Mount Taishan at the south, and the impervious Qiguang Fault at the north (figure 3). The maximum circulation depth of regional groundwater in Jinan is calculated to be 1300-1900 m [14]. Given the rock permeability decreasing with depth, the depth of 2000 m is set as impervious basement of the model.

Figure 3. Schematic diagram of the generalized model structure and boundary conditions.

The model domain is discretized into triangular meshes, with the maximum element size of 30 m. The mesh has 173960 nodes and 342648 elements. The top boundary for the groundwater flow model is specified hydraulic heads and three other boundaries are impervious. For the age mass transport model, the impervious boundaries correspond to the zero age mass flux, the recharge zones on the top correspond to the zero age mass, and the discharge zones on the top correspond to the zero dispersive age mass flux.

The effective porosity ($\theta$), hydraulic conductivity ($K$) and dispersity are the principal parameters for the subsurface flow and age mass transport model. The parameters are mainly acquired from numerical simulation and pumping tests as well as tracing experiments conducted in the previous study [9,15,16]. Measured groundwater age and flow paths determined by the hydrochemical and isotopic data are also used to calibrate model parameters.

Figure 4. The relationship between hydraulic conductivity and depth in Ordovician limestone aquifer. The karst development degree is represented by the percentage of boreholes discovering caves in Jinan. The permeability decaying tendency is approximately represented by the attenuation of karst development with depth.
Since the permeability of karst aquifer is controlled by the degree of karst development, the attenuation of karst development with depth can approximately represent the permeability decaying tendency. The hydraulic conductivity of Ordovician limestone aquifer exhibits exponential distribution with decay exponent of 0.003 m\(^{-1}\) (figure 4).

The calibrated horizontal hydraulic conductivity \(K_x\) and effective porosity \(\theta\) are listed in table 1. The anisotropy ratio \(K_x/K_z\) is set as 50, and longitudinal dispersity being 80 m, lateral dispersity being 8 m, which make the simulation results more reasonable. The longitudinal dispersity is about 1/1000 of the cross-section length, coinciding with Castro and Goblet and Jiang et al [6,7].

| Strata          | Horizontal Hydraulic Conductivity \(K_x\) (m/d) | Effective Porosity \(\theta\) (-)          |
|-----------------|-----------------------------------------------|--------------------------------------------|
| Q               | 15                                            | 0.01                                       |
| C+P+T+J+N       | 0.01                                          | 0.01                                       |
| O               | 0.2–60                                        | 0.08 (above 1000 m depth)                  |
|                |                                               | 0.008 (below 1000 m depth)                |
| C               | 0.1                                           | 0.001                                      |
| Art             | 0.005                                         | 0.005                                      |
| \(\gamma\)     | \(10^{-6}\)                                   | \(0.0005\)                                |

5. Simulation results and discussion

5.1. Groundwater flow distributions

The distributions of subsurface flow system and groundwater age in the profile obtained from the above numerical model are exhibited in figure 5. The primary effect of water-table undulations on basinal water flow is the generation of hierarchically nested flow systems of different orders. Local flow system is distributed in the upper part, underlain by the intermediate and regional flow system.

Figure 5. The distributions of subsurface flow system and groundwater age in the profile A-A’.

Affected by the topographic relief of the mountain terrains in the south, groundwater mainly discharges at the lower area nearby, forming the local flow system. The local flow system is developed in the shallow part with short flow path and small penetration depth. The intermediate flow system is sourced from the southern piedmont, and then mainly flowing through the carbonate aquifers with longer flow paths. This subsystem is controlled by the macroscopic topography and permeability of
the aquifers. The regional flow system is characterized by the longest flow paths and smallest flow velocities. The regional landform features and large-scale hydrogeological structures dominate the development of this subsystem. The recharge of regional groundwater is from the southern ranges, and then flowing through deep fault and fracture zones with the longest flow paths and largest circulation depths driven by gravity.

The influence of lithologic changes on the groundwater flow system can be directly exhibited through the groundwater flowline. The flowline is refracted at the stratigraphic interface, and the larger lithologic difference between aquifers, the more obvious the flowline refraction is. The influence of gabbro rocks on the groundwater flow system is also exhibited in figure 5. Local and intermediate groundwater flow are resisted by the gabbro rocks and converged around the contact zone between limestone and igneous rocks. Then it may ascend in the form of springs in fissure-developed areas. Deep regional groundwater is forced to move downward and bypass the gabbro rocks, then entering the northern Jinan geothermal field.

5.2. Groundwater age distributions

The groundwater age simulation result is also exhibited in figure 5. Shallow Ordovician karst groundwater ages in discharge area (less than 200 m depth) vary between 10-30 a. Groundwater ages in the deep Ordovician thermal reservoir vary between 13-35 ka. The simulation result coincides with the measured groundwater age based on CFCs and $^{14}C$ dating method.

Groundwater age distribution is closely related to the flow system, with younger groundwater near recharge area and becoming older along the flow path. Abrupt change of age distribution can be found in the regional discharge area. Groundwater ages under the regional discharge area are generally larger than 40000 years, and even reaching 99000 years at the basin bottom. Thus it can be inferred that there exists stagnant zone under the regional discharge area.

An important characteristic of hierarchically nested flow system is the existence of stagnation points or stagnant zones between flow subsystems. The stagnation points can be divided into two types, i.e. basin-bottom stagnation points and internal stagnation points [17]. According to the simulation result (figure 5), three basin-bottom stagnation points SP$_{R1}$, SP$_{R2}$, SP$_{R3}$ are found in the groundwater flow system. SP$_{R1}$, SP$_{R2}$ are located at the bottom of regional groundwater divide and discharge area respectively. Groundwater at SP$_{R3}$ is the oldest in the basin, owing to its longest flow path and smallest velocity. SP$_{R2}$ is located at the bottom of gabbro rocks, reflecting the influence of gabbro rocks on groundwater flow system.

![Figure 6. Age profiles across the internal stagnation points SP$_{L1}$, SP$_{L2}$, SP$_{L3}$.](image-url)

Internal stagnation points SP$_{L1}$, SP$_{L2}$, SP$_{L3}$ are located inside the basin where the divergence and convergence of four flow subsystems coexist. The shape of groundwater age contours near the internal
stagnation points is similar to a ridge pointing to the discharge area.

Virtual boreholes penetrating stagnation points are used to exhibit the vertical groundwater age variations (figure 6). The profiles of groundwater age distribution exhibit that it reaches a local maximum near the stagnation points. When exceeding the influence zone of stagnation points, groundwater age changes become moderate. Groundwater below SP_{L1}, an internal stagnation point near the recharge area, becomes older with depth. But groundwater ages below SP_{L2} and SP_{L3}, internal stagnation points near the discharge area, firstly decrease and then increase with depth. This age change tendency is controlled by the regional groundwater flow direction. Regional groundwater in deep Ordovician aquifer is forced to move downward under the gabbro rocks, causing groundwater becoming older with depth. Then groundwater flow passes through the Ordovician aquifer and moves upward to the regional discharge area, which in turn leads to groundwater becoming younger with depth.

The heterogeneity of aquifer system can also influence the groundwater age profile, exhibiting the inflection point at the interface of different strata (figure 6). But the influence of lithologic change on groundwater age is much smaller than that of the special hydraulic property of stagnation points.

6. Conclusions
A 2-D coupled subsurface flow and age transport model is constructed to quantitatively analyse the distributions of subsurface flow system and groundwater age in the typical cross section in Jinan. The major findings of this study can be summarized as follows:

A hierarchically nested groundwater flow system, including local, intermediate and regional subsystems, develops in the study area. Topography and geological structure control the scale of groundwater flow hierarchies with different flow path length and circulation depth.

Groundwater age distribution is closely related to the subsurface flow system. The age of groundwater in different hierarchies is proportional to its flow path length and circulation depth. Local groundwater is much younger than the intermediate and regional groundwater. Abrupt change in groundwater age profile is the characteristic boundary between different groundwater flow systems.

Hydraulic heterogeneity is an important factor influencing groundwater flow and age distributions. Flowline is refracted at the stratigraphic interface and bypassing the impermeable gabbro rocks, which would further affect the groundwater age distribution.

Internal stagnation point is an important character of the nested groundwater flow system, and can be used to divide different flow hierarchies. Groundwater age abruptly changes and local maximum age value exists near the stagnation point.

The results of this study can contribute to the future application of groundwater flow system theory, such as interpreting groundwater tracer-age and hydrochemical evolution. The results of this study can also contribute to the groundwater resources management, especially guaranteeing the perennial outflow of karst springs in Jinan, and protecting groundwater quality. In the future, more hydrogeological work such as groundwater age dating and tracer test is needed to verify the numerical simulation results in this study.

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