Journal homepage: http://gwse.iheg.org.cn

Impact of water table on hierarchically nested groundwater flow system

Jun Zhang[1*], Rong-zhe Hou[1], Kun Yu[1], Jia-qiu Dong[1], Li-he Yin[1]

[1] *Key Laboratory of Groundwater and Ecology in Arid and Semi-arid Areas*, *Xi'an Center of Geological Survey*, *China Geological Survey*, *Xi'an* 710054, *China*.

Abstract: Water table configuration gives rise to hierarchically nested groundwater flow systems. However, there remains a lack of comprehensive understanding regarding the controlling factors of water table and its impact on flow systems. Moreover, it remains challenging to identify characteristics of water table space variation through limited groundwater observations at the regional scale. Based on two ideal two-dimensional cross-section analytical models, this study presents a simplified approach to preliminarily assess the nonlinear interactions between water table variation and three driving factors: Topography, geology and climate. Two criteria, C1 and C2, are utilized to address issues at different scales ranging from basin to local: (i) the influence of various factors on water table configuration; and (ii) the influence of water table on groundwater flow pattern. Then, the Ordos Plateau is taken as an example to explore the role of the water table in nested groundwater systems using the provided approach and criterion. The application of this approach in the Ordos Plateau demonstrates its appropriateness as a practical method for preliminarily determining the characteristics of water table configuration and its impact on flow systems. The study explores the mechanism influencing spatial variation in the water table and improves understanding of the interaction between topography, geology, and climate on groundwater flow patterns.

Keywords: Water table configuration; Groundwater flow pattern; Analytical models; Top boundary conditions; Ordos Plateau

Received: 13 Oct 2023/ Accepted: 12 Apr 2024/ Published: 10 Jun 2024

Introduction

The theory proposed by Tóth (1963) regarding the self-organization of groundwater flow in hierarchically nested systems is considered a cornerstone in the field of hydrogeology. Groundwater flow is an essential component of the hydrological cycle, intricately linked with geological, hydrogeological, chemical, and biological processes (Batelaan et al. 2003; Cardenas, 2007; Chen et al. 2021; Zhao et al. 2021; Liu et al. 2023; Lévesque, 2023). The delineation of hierarchically nested groundwater flow systems holds significant importance across various domains, including groundwater utilization and preservation, petroleum exploration (Tóth et al. 1988), geo-environmental engineering (Engelen and Jones, 1986; Engelen, 1996), ecohydrology (Batelaan et al. 2003), and long-term geological waste disposal (Tóth and Sheng, 1996; Tóth, 1999).

The spatial variability of the water table leads to the development of hierarchically nested groundwater flow systems within sedimentary aquifers (Jiang et al. 2012; Robinson and Love, 2013; Jiang et al. 2014). Characteristics of the water table configuration are the basis of the conceptualization of groundwater flow system (Freeze and Witherspoon, 1967; Fan et al. 2007; Maxwell and Kollet, 2008). Recharge areas with high water tables a typically coincide with topographic highs; while discharge areas with low water tables are align with topographic lows on a basin or regional scale. As such, groundwater flow driven by gravity is often referred to as "topography-driven groundwater flow" (Freeze and Cherry, 1979; Garven, 1995). The utilization of topography as a well-established upper boundary condition is a prevalent practice in the simulation of groundwater flow systems (Wang et al. 2016a; Wang et al.

---

[*] Corresponding author: Jun Zhang, *E-mail address*: zjun@mail.cgs.gov.cn

DOI: 10.26599/JGSE.2024.9280010

Zhang J, Hou RZ, Yu K, et al. 2024. Impact of water table on hierarchically nested groundwater flow system. Journal of Groundwater Science and Engineering, 12(2): 119-131.

2017). Initially, analytical solutions of theoretical models incorporating sinusoidal undulating top boundary conditions are employed. Subsequently, numerical models featuring a specified head of arbitrary shape are utilized to demonstrate hierarchical nesting of flow systems (Winter, 1976; Wörman et al. 2006; Jiang et al. 2011). Nevertheless, the hypothesis that topography is the primary driver of groundwater flow has not been extensively examined. In certain studies, there exists a limited or non-existent link between the water table and surface topography. Certain topographic valleys may not accurately correspond to actual discharge areas (Desbarats et al. 2002; Marchetti and Carrillo, 2014). Moreover, several studies have demonstrated that employing terrain as a setting for top boundary conditions always result in high fluxes at the top boundary, which may exceed actual local precipitation or evapotranspiration. Some studies suggest that the prevalence of the Tothian pattern of nested groundwater flow systems may not be as widespread as previously assumed within the framework of idealized conceptual models (Dai et al. 2021). In this case, mathematical simulations with specified head top boundaries assumed by simplified representations of topography may not depict real groundwater flow.

Previous research has often utilized recharge rates as upper boundary conditions in simulating nested groundwater flow systems (Craig et al. 1988; Gleeson and Manning, 2008; Gleeson et al. 2011; Welch and Allen, 2012; Goderniaux et al. 2013; Liang et al. 2013). The recharge boundary conditions offer advantages over specified head boundary conditions due to their ability to ensure mass conservation. However, it is noteworthy that proper estimation of the recharge rate and distribution poses significant challenges in numerous instances.

Water table configuration is recognized to be influenced not only by topography but also by geology and climate (Haitjema and Mitchell-Bruker, 2005). Understanding the non-linear interactions between these factors remains critical, particularly given by the limited availability of groundwater observational data (Condon and Maxwell, 2015; Ning et al. 2019). Additionally, the regional-scale interaction mechanism among topography, geology and climate is rarely addressed, as is quantitative analysis of the impact of water table on hierarchically nested flow systems.

This study aims to examine the impact of upper boundary and water table on nested groundwater flow systems. Firstly, two ideal analytical models of two-dimensional cross-section are employed to propose a straightforward approach for discussing the control factors of water table configuration and its impacts on the flow system. Then, the Ordos Plateau is taken as an example to explore the role of the water table in nested groundwater systems. Through analytical solution experiments and a case study in the Ordos Plateau, it was aimed to examine spatial changes in water table elevation and improve the understanding of the regional-scale interaction mechanism between topography, geology, and climate for hierarchically nested groundwater flow.

1 Control factors of water table configuration

To reveal the factors influencing the variations in water tables in response to topographic fluctuations (Fig. 1), the Dupuit-Forchheimer model was employed to analyze water table dynamics within a regional unconfined aquifer system (Haitjema and Mitchell-Bruker, 2005). The maximum groundwater mound in the middle of the aquifer between the water bodies, denoted as Δh, can be expressed as

$$\Delta h = \frac{Wl^2}{mKH} \tag{1}$$

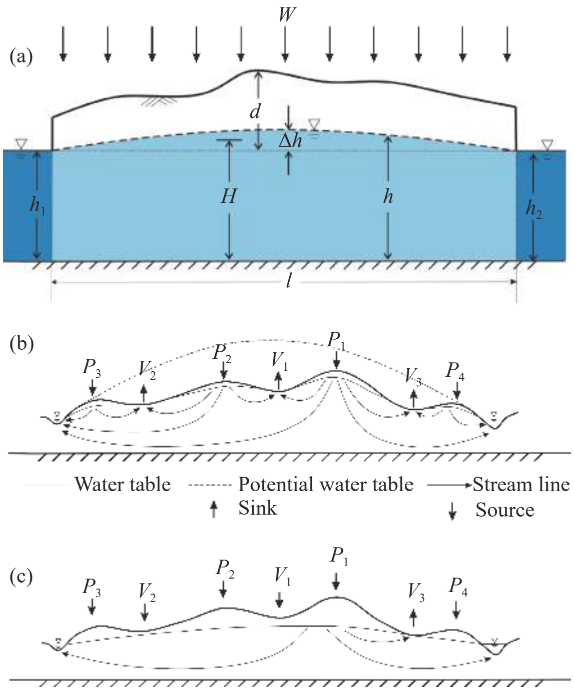

Fig. 1 (a) Groundwater mounding due to recharge may interact with the topography; (b) topography-controlled water table; (c) recharge-controlled water table (Haitjema and Mitchell-Bruker, 2005)

Where: W [m/d] is the areal recharge rate; l [m] is the distance between the streams, K [m/d] is the aquifer hydraulic conductivity; H [m] is the average aquifer thickness; and m is either 8 or 16, depending on whether the flow problem is one-dimensional or radial symmetric, respectively. Equation 1 indicates that the rise in water table is sensitive to the distance l between two surface water bodies. Given a specified aquifer geometry and thickness H, the groundwater mound Δh depends only on the dimensionless term, W/K, which is ratio of recharge rate to hydraulic conductivity. Next, the maximum terrain elevation difference, denoted as d, is defined as the largest disparity between the elevation of surface water bodies and the terrain surface, measured at the highest terrain elevation (Fig. 1a). Thus, by using the term $\Delta h/d$, the ratio of the maximum mounding to the maximum terrain difference, a decision criterion (C1) is presented as follows by Haitjema and Mitchell-Bruker (2005):

$$\frac{\Delta h}{d}=\frac{Wl^2}{mKHd}>1$$

$$\text{Water table is topography} - \text{controlled}$$

$$\frac{\Delta h}{d}=\frac{Wl^2}{mKHd}<1$$

$$\text{Water table is recharge} - \text{controlled}$$

The presence of two water bodies positioned at the boundaries of the Cross-Section Flow (CSF) may be attributed to regional sinks, such as rivers/channels or lakes/wetlands (Fig. 1a). In practical scenarios, these features might manifest as rivers or channels within the exorheic zone, or as lakes or wetlands within the endorheic region. As illustrated in Fig. 1b, the condition of topography-controlled water table could give rise to hierarchically nested flow systems, including: (1) two Regional Flow Systems (RFS) between the regional highest upland P1 and two water bodies; (2) an intermediate flow system between P2 and the left water body; and (3) eight Local Flow Systems (LFS) between the adjoining upland, the topographic valley, and the two water bodies. Although regional control by topography exists, the water table is not necessarily parallel to the local terrain surface and could be locally influenced by recharge. The local case will be discussed in section 3. From Fig. 1b to Fig. 1c, it can be inferred that a decrease in water mounding Δh represents the water table shifting from a topography-controlled to a recharge-controlled state at the regional scale. In this process, the topographic valleys V_1 and V_2 undergo a transformation from actual sinks to sources, resulting in the development of groundwater flow systems from (i) local, intermediate, and regional; to (ii) local and regional, and finally; to (iii) simple regional systems (not displayed, similar to the case of Fig. 1a), whereas the lowest sink remains the only active site of regional discharge.

2 Impact of water table configuration on LFS

As shown in Fig. 2, the Local Flow Systems (LFS) within the Regional Flow Systems (RFS), as discussed in the previous section in the local case, can be approximated as Cross-Section Flow (CSF) in an unconfined aquifer between two water bodies. Note that this approximation assumes that the two water bodies situated on either side of the boundaries completely penetrate the unconfined aquifer instead of the LFS in RFS. The purpose of this approximation is to solve the flow equation using the Dupuit assumption.

In the unconfined aquifer, the shape of the water table determines the flow distribution, which, in turn, is influenced by the flow distribution. To solve the flow equation, Dupuit (1863) assumed that: (1) the water table or free surface was only slightly inclined, and (2) the flow was consistently horizontal and uniform across every vertical section. With the Dupuit assumptions, two equations can be derived:

$$h_x{}^2=h_1^2-\frac{(h_1^2-h_2^2)}{l}+\frac{W}{K}(l-x)x \tag{2}$$

$$q_1=\frac{K(h_1^2-h_2^2)}{2l}-\frac{Wl}{2} \tag{3}$$

Where: h_x [m] is the height of water table at any distance x from the left origin; h_1 [m] and h_2 [m] are the height of water table at the two water bodies; l [m] is the horizontal distance between two water bodies; W [m/d] is the recharge rate; K [m/d] is the hydraulic conductivity; and q_1 [m^2/d] is the flow rate per unit width from the left to right boundary.

Equation 2 predicts the water table position at any given point along the section, while Equation 3 determines the flow rate of any given portion between two water bodies. However, these equations are acceptable if only vertical flow groundwater can be disregarded, which is reasonable for the flat slope of the water table except near the outflow (Muskat, 1938). For most large groundwater basins, the regional slope of the water table is minimal, and horizontal flows dominate the groundwater flow. Therefore, using Equations 2

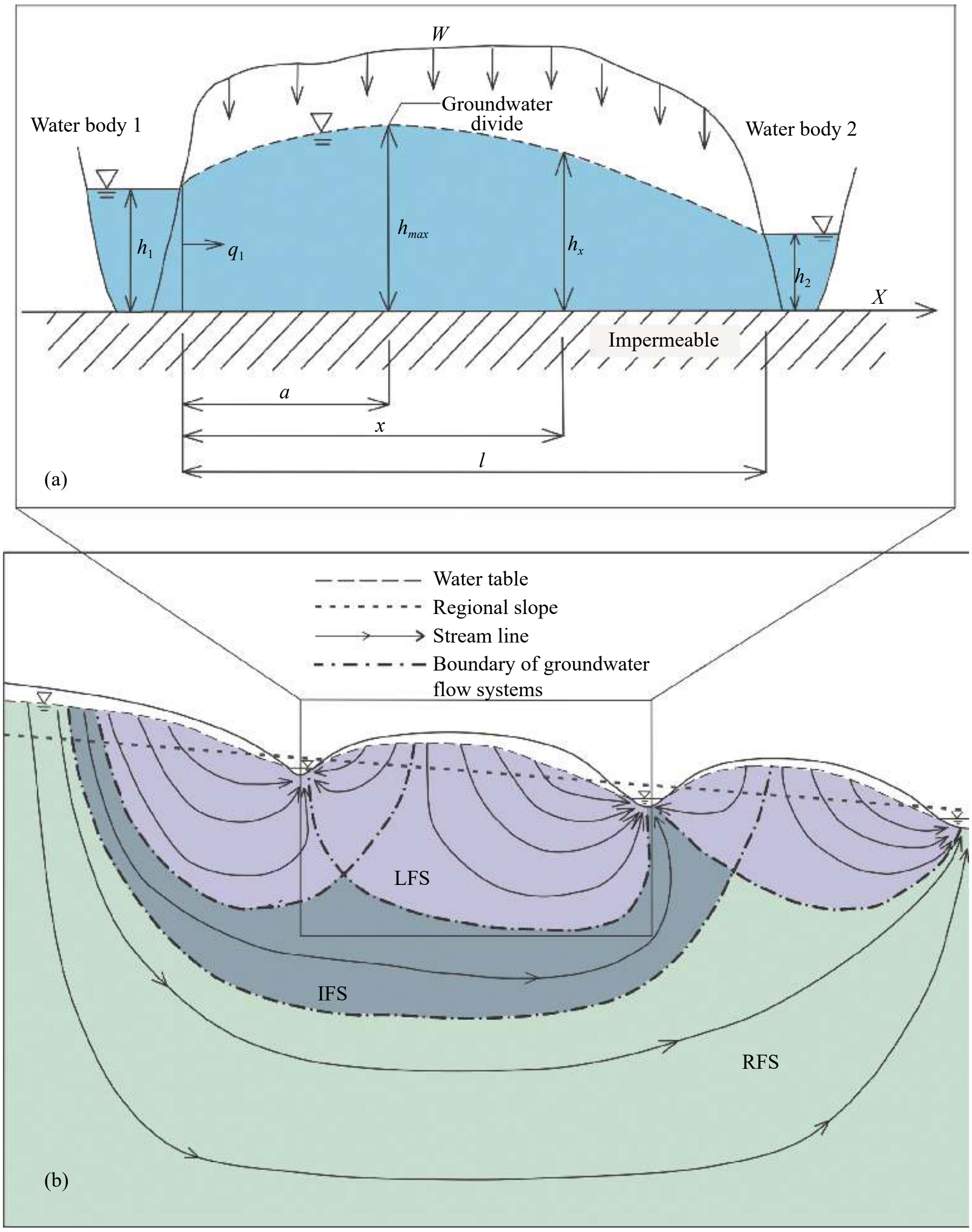

Fig. 2 (a) CSF in an unconfined aquifer between two water bodies; (b) LFS in RFS, which IFS represents the intermediate flow system

and 3 to determine the water table configuration and flow rate is deemed rational.

Given the heights of water table values of the two water bodies, h_1, and h_2, and a certain horizontal distance between them, l, to Equation 2, the water table at any position of section h_x is determined by the dimensionless term, W/K. When $h_1=h_2$, Equation 2 can be expressed as:

$$(h_x+h_1)(h_x-h_1)=\frac{W}{K}(l-x)x \tag{4}$$

Here, h_x-h_1 is the groundwater mound Δh as presented in Equation 1 when x equals $l/2$. h_x+h_1 can be approximated as $2H$ when Δh is much less than the aquifer thickness H. In this case, Equation 4 becomes Equation 1, which represents Haitjema and Mitchell-Bruker's model (Fig. 1). Therefore, Equation 1 is a special case of Equation 2 when h_1 equals h_2.

It is defined that the slop of the water table, I, and the average thickness of aquifer, H, in CSF:

$$I=\frac{h_1-h_2}{l} \tag{5}$$

$$H=\frac{h_1+h_2}{2} \tag{6}$$

Taking CSF within the context of a regional system or basin, the slop of water table I can be considered as the regional slop of water table within the RFS and the regional slope of basin.

The average thickness of aquifer H can be regarded as the depth of the LFS, and l can be represented as the horizontal extent of the LFS.

By combining Equations 5 and 6 with Equation 3, the following equation can be derived:

$$q_1 = KIH - \frac{Wl}{2} \tag{7}$$

In the case of $q_l < 0$ and $q_l > 0$, representing the flow direction to the left and right, respectively, Equation 7 can be expressed as:

$$\frac{Wl}{2KHI} > 1 \quad (q_1 < 0) \tag{8}$$

$$\frac{Wl}{2KHI} < 1 \quad (q_1 > 0) \tag{9}$$

At the regional scale, Equation 8 suggests the development of a groundwater divide in CSF, indicating the presence of LFS within RFS. Conversely, Equation 9 indicates the absence of a groundwater divide in CSF, implying the absence of LFS within RFS. Therefore, Equations 8 and 9 can serve as a straightforward decision criterion (C2) for predicting the occurrence of LFS within RFS on the regional or basin scale. Assuming that the water divide is located midway between two LFS drainages, the distance between two the water bodies l is the horizontal extent of LFS.

According to decision criterion C2, the development of LFS is influenced by five factors, including area recharge rate W, hydraulic conductivity of aquifer K, horizontal extent of LFS l, circulation depth of LFS H, and average regional slope of basin I. The horizontal extent and circulation depth of LFS (l and H) and the average slope of basin (I) are mainly controlled by the basin topography. Moreover, the area recharge rate W and hydraulic conductivity K are mainly controlled by climatic conditions and aquifer lithology. Qualitatively, it is not conducive to the development of a LFS when the regional slope of water table or average slope of the basin I increases and other factors remain unchanged, which is consistent with the conclusion by Tóth (1963). Conversely, an increase in recharge rate or a decrease in hydraulic conductivity, with unchanged basin topography, is conducive to LFS development, consistent with the conclusion by Provost and Voss (2001) and Liang et al. (2010).

After manipulation, Equation 8 can be rewritten as:

$$l > \frac{2HIK}{W} \tag{10}$$

$$W > \frac{2HIK}{l} \tag{11}$$

It can be seen from Equation 10 that the minimum horizontal extent of the local system l can be determined by a groundwater basin with certain climatic conditions (characterized by W), geology (H, K) and topography (I). Similarly, Equation 11 suggests that the minimum recharge rate W allowing LFS development can be determined by a groundwater basin with specific geological (H, K) and topographical (characterized by I, l) conditions.

3 Case study

3.1 Study area

The Ordos Basin, the second-largest sedimentary basin in northwestern China, is abundant in fossil fuel and mineral resources. The economic development of the Ordos Basin is constrained by its dry to semi-arid environment, which results in limited water supplies and vulnerable ecosystems. Groundwater plays a critical role as a water resource for both human consumption and vegetation sustenance within the region. Understanding groundwater flow patterns is crucial for promoting sustainable development of the resources and safeguarding the ecology in the Ordos Plateau. The Ordos Plateau, situated north of the Ordos Basin and south of the Yellow River, spans approximately 360 km from north to south and 210 km to 260 km from east to west. The elevation of the Ordos Plateau ranges from 1,400 m to 1,500 m in the central Sishi Ridge to 1,100 m to 1,200 m above sea level in the eastern, western, and northern margins. The Baiyu Mountain, located at the southern boundary, exhibits altitudes ranging from 1,500 m to 1,800 m above sea level (Fig. 3). The plateau exhibits a regionally sloping and locally undulating geomorphology. The study region is divided into three groundwater basins by the Sishi Ridge and Xinzhao Ridge, designated based on the three exorheic rivers that discharge into the Yellow River: The Dosit groundwater basin, the Muolin groundwater basin, and the Wuding groundwater basin. There is a large internal drainage system called the Ordos Endorheic Region. This region is characterized by numerous small catchments, which have resulted in the formation of lakes within topographic depressions. According to Ma et al. (2024), the landscapes in the Ordos Endorheic Region can be classified under the glacier and dune terrain category, while the three exorheic river watersheds can be categorized as riverine terrain. These rivers and lakes are fed by ground-

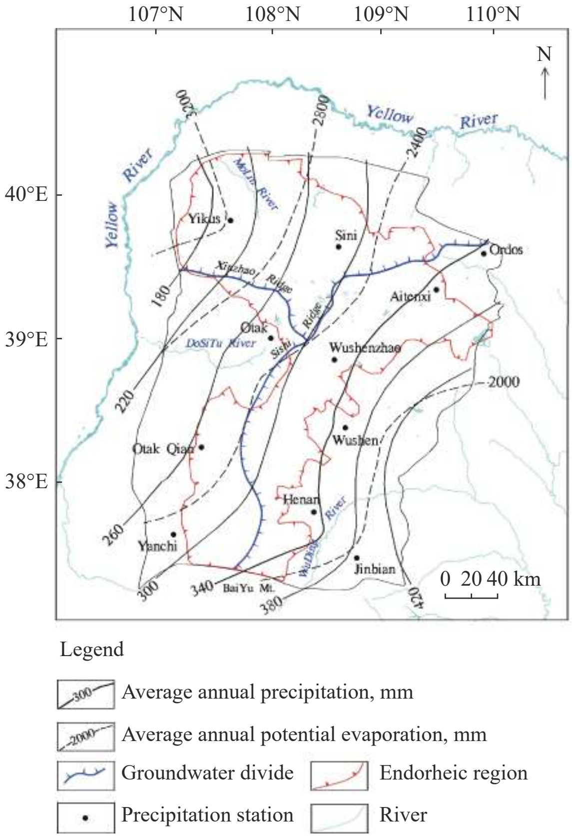

Fig. 3 Map of the Ordos Plateau showing average annual precipitation, potential evapotranspiration, endorheic region and groundwater divide

water, which are significant features in the study area.

The climate inside the Ordos Plateau is primarily classified as arid to semi-arid, with average annual precipitation gradually decreasing from approximately 420 mm in the southeastern region to around 160 mm in the northwestern region. Precipitation mainly occurs during the summer and autumn seasons, with a notable concentration of approximately 60%–80% observed during the months of July and September. The average annual potential evaporation rate is very high, varying from around 2,000 mm to 3,200 mm.

The aquifer in the Ordos Plateau is composed of a thick layer of Cretaceous sandstone, which is poorly consolidated and occasionally contains clay lenses. This unconfined aquifer *i* has a maximum thickness of around 1,000 m (Hou et al. 2010). The Cretaceous sandstone can be classified into three distinct groups: The Luohe Group (K_1l), the Huanhe Group (K_1h), and the Luohandong Group (K_1lh), from the bottom to the top. Despite the presence of clay lenses, the Cretaceous sandstone aquifer exhibits macroscopic homogeneity, particularly within the same faces of a group. This aquifer is widely distributed above a layer of thinly consolidated Quaternary sediments, which facilitate the infiltration of rainfall. The aquifer also overlays the Jurassic sandstone, known for its coal deposits, with the upper section assumed to be an aquitard due to its low permeability (Hou et al. 2010). The Ordos Plateau exhibits characteristics of an asymmetric syncline, with the eastern limb exhibiting a planar monoclinal configuration characterized by a westward dip ranging from 1 degree to 20 degrees, and the western limb displaying a more pronounced inclination. Faults within the Ordos Plateau are scarce, primarily found at the boundaries. Groundwater recharge primarily occurs through precipitation infiltration, while discharge mechanisms include potential evaporation, spring overflow, lake discharge, and artificial extraction.

Since 1999, a series of hydrogeological investigations have been conducted on the Ordos Plateau under the support of the China Geological Survey (Hou et al. 2010). It was found that Tóth's (1963) theory of groundwater flow system can explain the pattern of groundwater circulation in the area due to the undulating topography and relatively thick aquifer systems composed of macroscopically homogeneous sandstone.

Previous studies have revealed the development of hierarchically nested groundwater flow systems in the Ordos Plateau (Hou et al. 2010; Yin et al. 2010; Jiang et al. 2017; Zhang et al. 2021; Zhao et al. 2021), driven by topography. These studies have utilized various methods, including isotopic analysis, age dating, hydrogeochemical characterization, and theoretical modelling, to identify and characterize groundwater flow systems within the region. For example, Yin et al. (2010) first used the characteristics of δD and δ^{18}O in precipitation, groundwater, and surface water to identify the groundwater flow systems at different depths in the Ordos Plateau. Zhang et al. (2021) illustrated the accumulation of age mass around stagnation points based on ^{14}C age in two boreholes and simulated age in the Ordos Plateau. The basin-bottom hydraulic trap below the river and the boundaries between local and regional flows were identified based on the variations in apparent resistivity of the Cretaceous sandstone aquifer in the Ordos Plateau (Jiang et al. 2014). Hydrogeochemical characterization of groundwater flow systems revealed the mechanisms of groundwater evolution in the Dosit River Watershed discharge area in the Ordos Cretaceous Basin (Wang et al. 2015; Qu et al. 2023). The theoretical study on artesian flow conditions controlled by topography was examined in the Ordos Plateau (Wang et al. 2016b). The hierarchically nested groundwater flow systems in 3D are characterized using late-time peaks of residence time distributions in the Dosit River Watershed of the Ordos Plateau (Wang et al. 2016a). Previous research on the theory of regional groundwater flow has indicated that the Ordos Plateau presents an ideal location for investigating regional groundwater circulation patterns due to its unique geological and hydrological characteristics (Yin et al. 2010; Zhang et al. 2021) .

3.2 Water table configuration in Ordos Plateau

In this study, criterion C1 was utilized to assess whether the water table in the Ordos Plateau is primarily controlled by topography or recharge. The case on the regional scale was first reviewed. The Sishi Ridge acts as the regional water divide, positioned midway between two regional drainages in the Ordos Plateau. The distance between these regional water divides and the adjacent regional drainages on the east or west sides of the Ordos Plateau is about 120 km. So, the distance l for criterion C1 is around 240 km. The thickness of the unconfined aquifer, consisting of poorly-consolidated Cretaceous sandstone with sporadic clay lenses, ranges from 600 m to 1,000 m. For the calculation, an average aquifer thickness (H) of 800 m and an average aquifer hydraulic conductivity (K) are assumed for the Cretaceous sandstone of 0.3 m/d (Yin et al. 2010). The maximum terrain rise (d) is about 250 m according to Digital Elevation Models (DEM) of the Ordos Plateau. Additionally, the recharge rate (W) as 1.23×10^{-5} m/d was calculated based on the precipitation amount (300 mm/a) multiplied by the average precipitation recharge coefficient of 0.15 (Yin et al. 2010; Zhang et al. 2019). With these numerical values, the calculation result of $\Delta h/d$ is determined to be 14.8 for a specific value of m, namely 8. This finding provides an explanation for the topography-controlled water table in the Ordos Plateau at the basin scale.

The water table contours map of the Ordos Plateau was generated using groundwater level data collected from 930 wells during the period of 2006 to 2008, as plotted in Fig. 4. This map shows that the configuration of water table resembles the topography but is smoother. A linear equation, $h = 0.9395Z + 64.88$, with a R^2 value of 0.92, reasonably approximates the relationship between the elevation of the water table (h) and land surface (Z). The contours of the water table exhibit a closed configuration in the vicinity of lakes at the basin scale, indicating groundwater movement towards the lake in the shallow region, forming local flow systems that discharge into the lake. Conversely, open contours in areas of elevated topography suggests groundwater movement towards catchments located in lower areas, facilitating the formation of regional flow systems.

At the local scale, the distance (l) ranges from 5.51 km to 24.83 km, with an average value of 9.98 km based on field investigation and hydrological statistical analysis of surface watersheds using DEM data. The average vertical circulation depth (H) of local flow systems in the Ordos Plateau is determined to be 150 m (Yin et al. 2010). The maximum terrain rises d ranges from 80 m to 150 m based on local topographic relief. With the same values for m, K and W, the ratio of groundwater mounding to maximum terrain rise ($\Delta h/d$) ranges from 0.069 to 3.7. This indicates that water tables at the local scale are influenced either by recharge or topography, depending on local topographic features such as relief, slope, and horizontal range of the local drainage basin.

The analysis suggests that water table configuration in the Ordos Plateau depends on topography, geology, and climate (Haitjema and Mitchell-

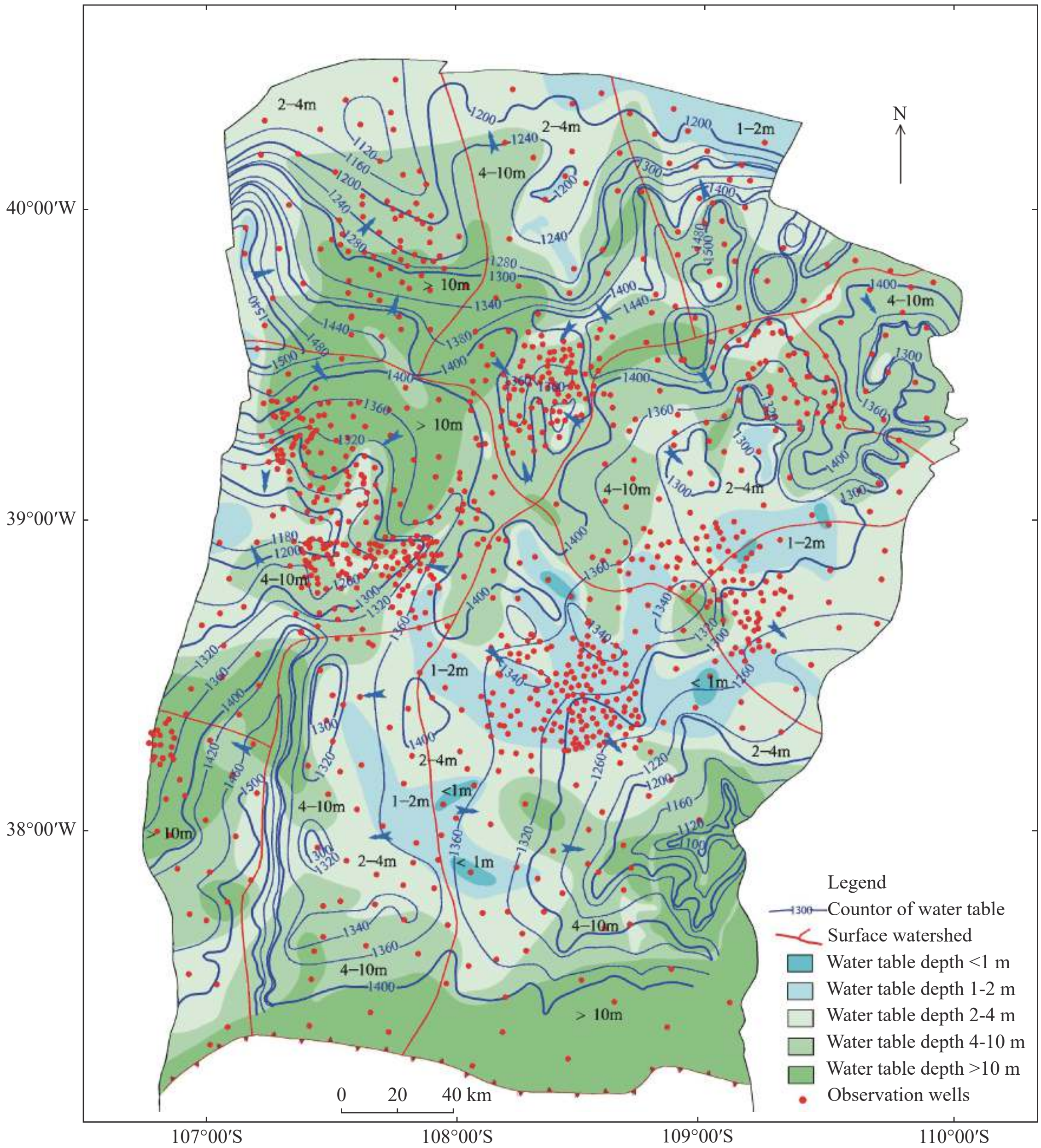

Fig. 4 The contours map of water table elevation and water table depth of 2006 to 2008

Bruker, 2005; Gleeson et al. 2011), including factors such as local and regional topography, aquifer thickness, hydraulic conductivity, precipitation, and surface infiltration conditions.

Criterion C1 demonstrates reasonable performance in the case study of the Ordos Plateau, characterized by topography-driven hierarchically nested groundwater flow systems. Despite being situated in an arid and semi-arid region with low precipitation levels, the Ordos Plateau possesses aeolian sands with high permeability, allowing effective water retention and infiltration. This unique hydrogeological condition underscores the significance of topography in influencing water table configuration in the region.

3.3 Development of local flow system in the Ordos Plateau

In this section, it is assessed that the development of Local Flow System (LFS) in the Ordos Plateau using decision criteria C1 and C2. If the water table is topography-controlled, indicating interaction with the topography, LFS development occurs. Conversely, if the water table is recharge-controlled locally, with the water mounding lower than the terrain, decision criterion C2 can be used to estimate the potential impact of water table configuration on LFS.

As mentioned above, area recharge rate W is 1.23×10^{-5} m/d, the horizontal extent of LFS l

ranges from 5.51 km to 24.83 km (take the minimum of 5.51 km), K is 0.3 m/d, H for local flow systems is 150 m. As shown in Fig. 2b, the regional slope of water table I is approximately equal to the topographic slope. So, I, calculated by the maximum terrain elevation difference (240 m) over the average horizontal distance between the regional water divide of Sishi Ridge and the regional drainages on the east or west sides of the Ordos Plateau (120 km), is 0.002. With the above terms, the left side of Equation 8 equals 3.77, which indicates that LFS is commonly present in RFS in the Ordos Plateau.

Given the parameters (H=150 km, I=0.002, K=0.3 m/d, W=1.23×10^{-5} m/d), Equation 10 indicates that the minimum horizontal extent for local system development should be greater than 1.44 km under the present climate and geological conditions of the Ordos Plateau.

For Equation 11, with the specified range of values for l (5.51 km and 24.83 km), and other constants, the recharge threshold recharge rate is calculated as $W > 3.27\times10^{-5}$ m/d and $W > 7.25\times10^{-6}$ m/d. Further analysis involves considering the average annual precipitation (P) of the Ordos Plateau, calculated as > 79.5 mm/a and > 17.6 mm/d, using the average precipitation recharge coefficient of 0.15. This suggests that LFS appear when $P > 79.5$ mm/a and disappear when $P < 17.6$ mm/a in the Ordos Plateau. Considering the variability from arid climate conditions of low recharge amount, the analyses are of significance to improve understanding of the impact of extreme climate change on groundwater flow systems.

4 Discussions

Criteria C1 and C2 are derived from analytical models under conditions where the water table is not specified, which evaluated factors influencing water table configuration and groundwater flow pattern.

4.1 Identification of control factors of water table configuration

Criterion C1 assesses whether the groundwater flow system has a potential hierarchically nested structure. Recharge-controlled water tables typically demonstrate horizontal flow in regional flow systems, while topography-controlled water tables contribute to the formation of local flow systems. Tóth has highlighted that deep aquifers with topography-controlled water tables tend to develop hierarchically nested flow systems. Therefore, C1 provides an initial evaluation of the water table configuration, even in the absence of water table measurements. In the case study of the Ordos Plateau, criterion C1 shows successful application and robust performance. The results confirm that water table configuration in the Ordos Plateau is generally dependent on factors such as topography, thickness, hydraulic conductivity, precipitation, and surface infiltration conditions. Notably, topography is more important in influencing the water table configuration than others. Criterion C1 shows reliable performance for preliminary estimation of water table configuration in the Ordos Plateau and holds potential applicability to similar areas lacking water table data. While this assessment may lack absolute accuracy, it provides a preliminary analysis of regional groundwater flow patterns.

4.2 Formation conditions of local flow system development

The second issue is the key point of groundwater flow system theory as discussed by Tóth (1963), which is based on an ideal two-dimensional homogeneous and isotropic analytical model. While early studies, including Tóth's, relied on specific upper boundary conditions to represent the water table, recent research has employed topographic relief as an approximation (Zech et al. 2015). However, the water table, as a part of the solution in our analytical models, is treated as a variable function influenced by factors such as recharge (W), geology (H, K), and topography (I, l). Therefore, criterion C2 provides a new approach to understanding the relationships between groundwater behavior, water table configuration, and groundwater flow pattern, considering the three primary drivers: recharge, aquifer hydraulic conductivity, and topography. The findings suggest that the local flow systems are commonly developed in the Ordos Plateau. The minimum horizontal extent of local system development should be greater than 1.44 km under present climate conditions, which is consistent with the results of field surveys. This underscores the applicability of criterion C2 as a concise method for preliminary determination of the minimum horizontal extent and formation conditions of local flow systems. Moreover, criterion C2 can establish the precipitation threshold for the appearance of local flow systems, which shows the critical impact of climate change on groundwater flow systems in the Ordos Plateau.

4.3 Limitation and further work

The approach in this study is based on the principles of homogeneous and isotropic media and the Dupuit assumption. These assumptions are deemed appropriate under the condition where vertical groundwater flow can be neglected. The validity of these approximations depends on aquifer geometry and the degree of vertical anisotropy. While the Dupuit assumption holds when the distance l between hydrological boundaries significantly exceeds aquifer thickness, aquifer anisotropy can introduce errors in its application.

Future investigations will focus on exploring the effects of aquifer geometric conditions, heterogeneity, and anisotropy on flow patterns. Furthermore, our model utilizes the saturated flow model, with the water table serving as the upper boundary. However, this choice presents challenges in accurately capturing the complex dynamics between groundwater levels, land use, land cover change, and climate change. Consequently, a variably saturated flow model must integrate groundwater flow process with various external factors that influence water table configuration, such as overland flow, infiltration, evaporation, and transpiration.

5 Conclusion

This study offers a straightforward approach to estimating the impact of the water table on hierarchically nested groundwater flow system, utilizing two ideal analytical models of two-dimensional cross-section under the condition of an unspecified water table. These models, Criterion C1 and C2, serve distinct purposes. Criterion C1 is for identifying the control factors of water table configuration. The results based on C1 confirm that the configuration of the water table is generally dependent on factors such as topography, aquifer thickness and hydraulic conductivity, precipitation levels, and surface infiltration conditions. Notably, topography emerges as the more important other factors shaping the groundwater table in the Ordos Plateau. Criterion C2, on the other hand, is employed to predict the occurrence of Local Flow Systems (LFS) within Regional Flow System (RFS) on a regional or basin scale. According to C2, the development of LFS is influenced by five factors: Area recharge rate, hydraulic conductivity, horizontal extent of LFS, circulation depth of LFS, and the average regional slope of the basin. The results indicate a common occurrence of local flow system in the Ordos Plateau, with a minimum horizontal development extent of over 1.44 km under present climatic conditions. The specific interplay of climate, topography, and lithology significantly influences the development and evolution of the groundwater flow systems, affecting the control of the groundwater table. This study shed light on the mechanism influencing spatial variations in the water table, thereby enhancing our understanding of the factors affecting hierarchically nested groundwater flow. Moving forward, it is imperative to focus on investigating the effects of aquifer geometric conditions, heterogeneity, and anisotropy on the water table and flow patterns in future research endeavors.

Acknowledgments

This study was funded by the Inner Mongolia Autonomous Region Science and Technology Program (2021GG0198), Shaanxi Science, Technology Department (No. 2021ZDLSF05-01, 2022SF-327) and China Geological Survey (DD20190351, DD20221751).

References

Batelaan O, De Smedt F, Triest L. 2003. Regional groundwater discharge: Phreatophyte mapping, groundwater modelling and impact analysis of land-use change. Journal of Hydrology, 275: 86−108. DOI：10.1016/S0022-1694(03)00018-0.

Condon LE, Maxwell RM. 2015. Evaluating the relationship between topography and groundwater using outputs from a continental-scale integrated hydrology model. Water Resources Research, 51(8): 6602−6621. DOI：10.1002/2014wr016774.

Cardenas MB. 2007. Potential contribution of topography-driven regional groundwater flow to fractal stream chemistry: Residence time distribution analysis of Tóth flow. Geophysical Research Letters, 34(5): L05403. DOI：10.1029/2006GL029126.

Chen SM, Liu FT, Zhang Z, et al. 2021. Changes of groundwater flow field of Luanhe River Delta under the human activities and its impact on the ecological environment in the past 30 years. China Geology, 4(3): 455−462. DOI：10.31035/cg2021060.

Dai X, Xie Y, Simmons CT, et al. 2021. Understanding topography-driven groundwater flow using fully-coupled surface-water and groundwater modeling. Journal of Hydrology, 594: 125950. DOI：10.1016/j.jhydrol.2020.125950.

Desbarats AJ, Logan CE, Hinton MJ, et al. 2002. On the kriging of water table elevations using collateral information from a digital elevation model. Journal of Hydrology, 255(1): 25−38. DOI：10.1016/s0022-1694(01)00504-2.

Dupuit J. 1863. Etudes theoriques et pratiques sur le mouvement des eaux dans les canaux decouverts et a travers les terrains permeables avec des considerations relatives au regime des grandes eaux, au debouche a leur donner et a la marche des alluvions dans les rivieres a fond mobile. Dunod, éditeur. (in French)

Engelen GB. 1996. Hydrological systems analysis: Methods and applications, ed. F. H. Kloosterman. Dordrecht: Kluwer Academic.

Engelen GB, Jones GP. 1986. Developments in the analysis of groundwater flow systems. Iahs. Aghion, Philippe, Burgess, Robin and Mayer, C (Dis.), (1993) Fin.

Fan Y, Miguez-Macho G, Weaver CP, et al. 2007. Incorporating water table dynamics in climate modeling: 1. Water table observations and equilibrium water table simulations. Journal of Geophysical Research Atmospheres, 112(D10). DOI：10.1029/2006JD008111.

Forster C, Smith L. 1988. Groundwater flow systems in mountainous terrain: 1. Numerical modeling technique. Water Resources Research, 24(7): 999−1010. DOI：10.1029/WR024i007p00999.

Freeze RA, Cherry JA. 1979. Groundwater. Englewood Cliffs: Prentice-Hall.

Freeze RA, Witherspoon PA. 1967. Theoretical analysis of regional groundwater flow: 2. Effect of water-table configuration and subsurface permeability variation. Water Resources Research, 3(2): 623−634. DOI：10.1029/WR003i002p00623.

Goderniaux P, Davy P, Bresciani E, et al. 2013. Partitioning a regional groundwater flow system into shallow local and deep regional flow compartments. Water Resources Research, 49(4): 2274−2286. DOI：10.1002/wrcr.20186.

Gleeson T, Marklund L, Smith L, et al. 2011. Classifying the water table at regional to continental scales. Geophysical Research Letters, 38(5): L05401. DOI：10.1029/2010gl046427.

Gleeson T, Manning AH. 2008. Regional groundwater flow in mountainous terrain: Three-dimensional simulations of topographic and hydrogeologic controls. Water Resources Research, 44(10): 297−297. DOI：10.1029/2008WR006848.

Garven G. 1995. Continental-scale groundwater flow and geologic processes. Annual Review of Earth and Planetary Sciences, 23(1): 89−117. DOI：10.1146/annurev.ea.23.050195.000513.

Hou GC, Liang YP, Su XS, et al. 2010. Groundwater systems and resources in the Ordos Basin, China. Acta Geologica Sinica - English Edition, 82(005): 1061−1069. DOI：10.1111/j.1755-6724.2008.tb00664.x.

Haitjema HM, Mitchell-Bruker S. 2005. Are water tables a subdued replica of the topography? Ground Water, 43(6): 781−786. DOI：10.1111/j.1745-6584.2005.00090.x.

Jiang XW, Sun ZC, Zhao KY, et al. 2017. A method for simultaneous estimation of groundwater evapotranspiration and inflow rates in the discharge area using seasonal water table fluctuations. Journal of Hydrology, 548: 498−507. DOI：10.1016/j.jhydrol.2017.03.026.

Jiang XW, Wan L, Wang JZ, et al. 2014. Field identification of groundwater flow systems and hydraulic traps in drainage basins using a geophysical method. Geophysical Research Letters, 41(8): 2812−2819. DOI：10.1002/2014GL059579.

Jiang XW, Wan L, Ge SM, et al. 2012. A quantitative study on accumulation of age mass around stagnation points in nested flow systems. Water Resources Research, 48(12): W12502. DOI：10.1029/2012wr012509.

Jiang XW, Wang XS, Wan L, et al. 2011. An analytical study on stagnation points in nested flow systems in basins with depth-decaying hydraulic conductivity. Water Resources Research, 47(1): 128−139. DOI：10.1029/2010WR009346.

Liu J, Cheng YP, Zhang FE, et al. 2023. Research hotspots and trends of groundwater and ecology studies: Based on a bibliometric approach. Journal of Groundwater Science and Engineering, 11(1): 20−36. DOI：10.26599/JGSE.2023.9280003.

Lévesque Y, Romain C, Julien W. 2023. Using geophysical data to assess groundwater levels and the accuracy of a regional numerical flow model. Hydrogeology Journal, 31(2): 351−370. DOI：10.1007/s10040-023-02591-z.

Liang X, Quan D, Jin M, et al. 2013. Numerical simulation of groundwater flow patterns using flux as upper boundary. Hydrological Processes, 27(24): 3475−3483. DOI：10.1002/hyp.9477.

Liang X, Liu Y, Jin M, et al. 2010. Direct observation of complex Tóthian groundwater flow systems in the laboratory. Hydrological Processes, 24(24): 3568−3573. DOI：10.1002/hyp.7758.

Ma Z, Wang W, Zhang Z, et al. 2024. River–groundwater interactions in the arid and semi-arid areas of northwestern China. Hydrogeology Journal, 32: 37−57. DOI：10.1007/s10040-023-02691-w.

Marchetti ZY, Carrillo Rivera JJ. 2014. Tracing groundwater discharge in the floodplain of the parana river, Argentina: Implications for its biological communities. River Research and Applications, 30(2): 166−179. DOI：10.1002/rra.2629.

Maxwell RM, Kollet SJ. 2008. Interdependence of groundwater dynamics and land-energy feedbacks under climate change. Nature Geoscience, 1(10): 665−669. DOI：10.1038/ngeo315.

Muskat M. 1938. The flow of homogeneous fluids through porous media. Soil Science, 46(2): 169. DOI：10.1097/00010694-193808000-00008.

Ning TS, Zhou S, Chang FY, et al. 2019. Interaction of vegetation, climate and topography on evapotranspiration modelling at different time scales within the Budyko framework. Agricultural and Forest Meteorology, 275: 59−68. DOI：10.1016/j.agrformet.2019.05.001.

Provost AM, Voss CI. 2001. Recharge-area nuclear waste repository in southeastern Sweden. Demonstration of hydrogeologic siting concepts and techniques. Sweden. SKI Report, 1: 44.

Qu S, Wang C, Yang N, et al. 2023. Large-scale surface water-groundwater origins and connectivity in the Ordos Basin, China: Insight from hydrogen and oxygen isotopes. Environmental Research, 236: 116837. DOI：10.1016/j.envres.2023.116837.

Robinson NI, Love AJ. 2013. Hidden channels of groundwater flow in Tóthian drainage basins. Advances in Water Resources, 62(part A): 71−78. DOI：10.1016/j.advwatres.2013.10.004.

Tóth J. 1999. Groundwater as a geologic agent: An overview of the causes, processes, and manifestations. Hydrogeology Journal, 7(1): 1−14. DOI：10.1007/s100400050176.

Tóth J, Sheng G. 1996. Enhancing safety of nuclear waste disposal by exploiting regional groundwater flow: The recharge area concept. Hydrogeology Journal, 4(4): 4−25. DOI：10.1007/s100400050252.

Tóth J, Back W, Rosenshein JS, et al. 1988. Ground water and hydrocarbon migration. Hydrogeology, O-2. Geological Society of America. DOI：10.1130/DNAG-GNA-O2.485.

Tóth J. 1963. A theoretical analysis of groundwater flow in small drainage basins. Journal of Geophysical Research (1896-1977), 68(16): 4795−4812. DOI：10.1029/JZ068i016p04795.

Wang XS, Wan L, Jiang XW, et al. 2017. Identifying three-dimensional nested groundwater flow systems in a Tóthian basin. Advances in Water Resources, 108: 139−156. DOI：10.1016/j.advwatres.2017.07.016.

Wang JZ, Wörman A, Bresciani E, et al. 2016a. On the use of late-time peaks of residence time distributions for the characterization of hierarchically nested groundwater flow systems. Journal of Hydrology, 47−58. DOI：10.1016/j.jhydrol.2016.04.034.

Wang JZ, Jiang XW, Wan L, et al. 2016b. An analytical study on artesian flow conditions in unconfined-aquifer drainage basins. Water Resources Research, 51(10): 8658−8667. DOI：10.1002/2015WR017104.

Wang H, Jiang XW, Wan L, et al. 2015. Hydrogeochemical characterization of groundwater flow systems in the discharge area of a river basin. Journal of Hydrology, 527: 433−441. DOI：10.1016/j. jhydrol. 2015.04. 063.

Welch LA, Allen DM. 2012. Consistency of groundwater flow patterns in mountainous topography: Implications for valley bottom water replenishment and for defining groundwater flow boundaries. Water Resources Research, 48(5): W05526.1−W05526.16. DOI：10.1029/2011WR010901.

Wörman A, Packman AI, Marklund L, et al. 2006. Exact three-dimensional spectral solution to surface-groundwater interactions with arbitrary surface topography. Geophysical Research Letters, 33(7): 359−377. DOI：10.1029/2006GL025747.

Winter TC. 1976. Numerical simulation analysis of the interaction of lakes and ground water. US Geological Suru. Prof. Paper, 1001.

Yin LH, Hou GC, Tao ZP, et al. 2010. Origin and recharge estimates of groundwater in the ordos plateau, People's Republic of China. Environmental Earth Sciences, 60(8): 1731−1738. DOI：10.1007/s12665-009-0310-3.

Zhang J, Wang XS, Yin LH, et al. 2021. Inflection points on groundwater age and geochemical profiles along wellbores light up hierarchically nested flow systems. Geophysical Research Letters, 48(16): 1−10. DOI：10.1029/2020GL092337.

Zhao KY, Jiang XW, Wang XS, et al. 2021. Restriction of groundwater recharge and evapotranspiration due to a fluctuating water table: a study in the Ordos Plateau, China. Hydrogeology Journal, 29(2): 567−577. DOI：10.1007/s10040-020-02208-9.

Zhao W, Lin YZ, Zhou PP, et al. 2021. Characteristics of groundwater in Northeast Qinghai-Tibet Plateau and its response to climate change and human activities: A case study of Delingha, Qaidam Basin. China Geology, 4(3): 377−388. DOI：10.31035/cg2021053.

Zhang J, Wang WK. Wang XY, et al. 2019. Seasonal variation in the precipitation recharge coefficient for the Ordos Plateau, Northwest China. Hydrogeology Journal, 27(2): 801−813. DOI：10.1007/s10040-018-1891-2.

Zech A, Zehner B, Kolditz O, et al. 2015. Impact of heterogeneous permeability distribution on the groundwater flow systems of a small sedimentary basin. Journal of Hydrology, 532: 90−101. DOI：10.1016/j.jhydrol.2015.11.030.