Numerical Simulation for Impacts of Mountainous Tunnel Drainage on Groundwater Environment

Yong Xiao, Qichen Hao, Jingli Shao, Yali Cui and Qiulan Zhang

Abstract Mountainous tunnel drainage can cause various negative impacts on the groundwater environment and human life; as a result, it is necessary that the drainage is quantitatively estimated and minimized during the construction period. In this study, a numerical model was conducted to predict the influences of mountainous tunnel drainage on the groundwater environment in northern China. The results show that the drainage would change the groundwater flow field and form drawdown funnels; however, it would not cause regional groundwater drawdown. Besides, the discharge amount of springs was also affected by the tunnel drainage, and the maximum reducing amount was up to 25%. The storage resources of the aquifers were decreased under the effect of tunnel drainage. All negative influences could be gradually eliminated after the strong drainage. This research can provide effective methods to measure and decrease the impacts of tunnel drainage.

Keywords Numerical modelling · Groundwater · Tunnel drainage
Water inflow · Environment

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1 Introduction

As one of the most important parts of communication construction, a tunnel can significantly reduce the distance of transportation and improve traffic efficiency. However, the construction of a tunnel would cause a series of hydrogeological and environmental issues on groundwater dependent ecosystems [1]. Due to the increasing concern about environmental issues of large engineering projects, it is agreed that the effects of the tunnel on the quantitative and qualitative status of the water masses excavation should be avoided [2]. To weaken the impacts of tunnel excavation, measures should be taken appropriately so that the potential impacts can be correctly identified [3].

Currently, qualitative methods and quantitative methods are the main methods for identifying tunnel excavation impacts. The qualitative methods provide a basis for establishing objective conceptual hydrogeological models and determining the evolution trend of the groundwater environment under the condition of tunnel excavation. However, qualitative methods could not illustrate the degree of the impact on the water environment caused by tunnel excavation. While, quantitative methods can provide convincing information for estimating the effects. Numerical models are widely used to conduct quantitative methods. It could take all related variables into consideration, which is suitable for such complex hydrological conditions.

In this study, a 3-D numerical flow model was conducted to analyze the impacts of a mountainous tunnel construction on groundwater flow, private wells and springs. The results can provide reference to evaluate the influences of mountainous tunnel construction on the groundwater environment.

2 The Study Area

The tunnel is in a mountainous area in northern China (Fig. 1). The main stratums outcropping in this area include: Quaternary, Tertiary, Cambrian and Sinian strata (Fig. 2). The Quaternary deposits get thicker from north to south. The upper Quaternary deposits are Aeolian loess with vertical bedding joints, and the lower Quaternary deposits are solid clay with very poor permeability, leading to weak hydraulic connection between Quaternary strata and Tertiary strata. The upper Tertiary strata is mainly comprised by weakly cemented conglomerate, mudstone and sandy mudstone, while the lower Tertiary strata is mainly comprised of conglomerate, sand, sandstone and sandy mudstone. The lower Tertiary strata is the main groundwater aquifer. The Cambrian and Sinian strata develop fractures differentially; the Cambrian develop more fractures than Sinian strata.

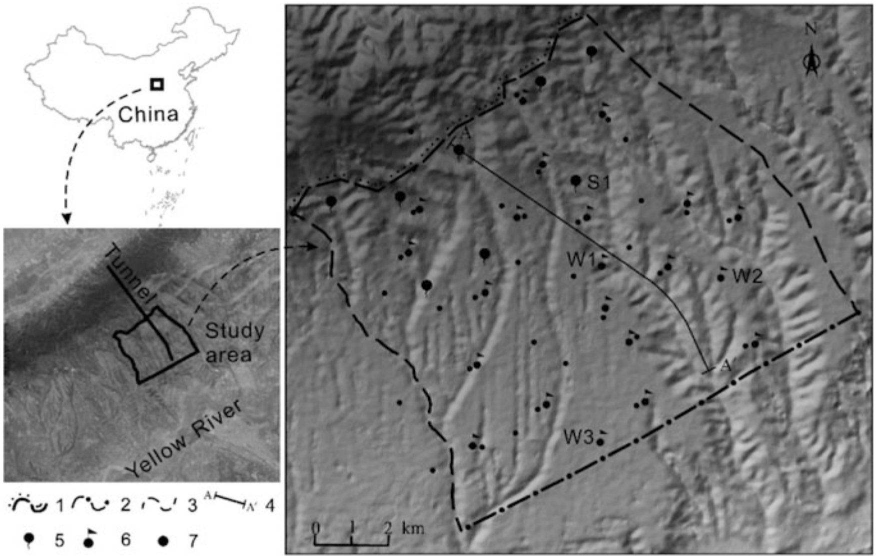

Fig. 1 Schematic map of model domain and location of observation wells. 1-Given flux boundary, 2-Given head boundary, 3-General head boundary, 4-Cross section, 5-Spring, 6-Well, 7-Village

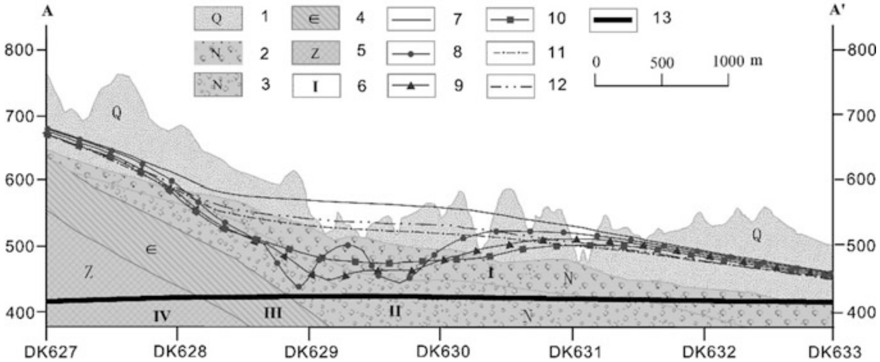

Fig. 2 Section view of lithology and groundwater level drawdown along the A-A'. 1-Quaternary deposits, 2-Upper Tertiary strata, 3-Lower Tertiary strata, 4-Cambrian strata, 5-Sinian strata, 6-Aquifer label, 7-Initial water level, 8-Water level in 6th month, 9-Water level in 12th month, 10-Water level in 18th month, 11-Water level in the 1st year after construction, 12-Water level in the 3rd year after construction, 13-Design tunnel

Under natural condition, groundwater is recharged by precipitation in the northern area, and flows from north to south. Groundwater discharges include springs, lateral outflow and evaporation and exploitation. However, the quantity of exploitation is less than 2000 m^3/d and is mainly exploited in the Quaternary aquifer and Tertiary aquifer.

3 Model Application

The conceptual model of the study area was established based on identification and characterization of the hydrogeological conditions. Due to the weak specific yield of rock in the northern area, the southern deposits area was taken as the modelling area. The northern boundary is between the bedrock and Quaternary deposits occurring area. The southern boundary is the Yellow River terraces. The dividing crests of two rivers in the east and west were set as general head boundaries. The northern boundary was defined as the given flux boundary, and the southern boundary was defined as the given (constant) head boundary. As the poor permeability of Quaternary deposits in the lower part, the strata below Quaternary deposits were taken as the modelling strata and divided into four aquifers. The upper Tertiary strata was defined as aquifer I, and the lower Tertiary strata was aquifer II. The Cambrian and Sinian strata are defined as aquifers III and IV, respectively.

The regional groundwater flow can be expressed as the equation described by Wang et al. [4]. Combing with the boundary conditions and initial conditions, the numerical model was established using Groundwater Model System software (GMS). The modelling area was discretized as a matrix of 205 rows × 210 columns × 4 layers. The total number of valid cells was 26,403 and each cell was 100 m × 100 m.

The numerical model was manually adjusted and calibrated using trial and error method. As shown in Fig. 3, there are ten observed wells with the fitting error less than 1 m, and seven observed wells with the fitting error ranging between 1 and 2 m. The number of wells with the fitting error between 2 and 3 m is three. Only one well has the fitting error over 3 m. The four kinds of observation wells account for 47.6%, 33.3%, 14.3% and 4.8% of the total observation wells, respectively. The results suggest that the model can reflect the objective hydrogeological

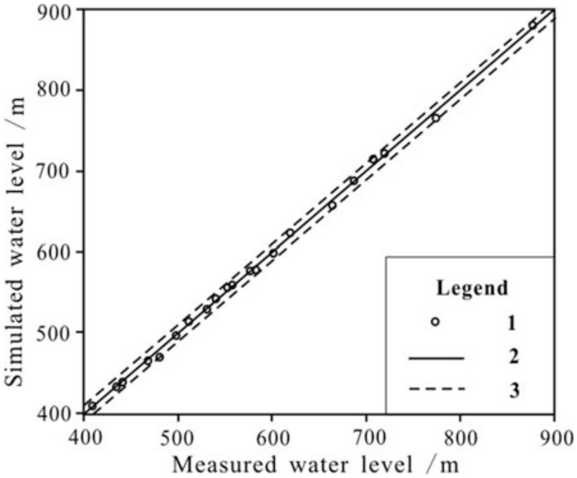

Fig. 3 Comparison chart of simulated and measured water level. 1-Wells, 2-Diagonal line, 3-Error line (±3 m)

condition of the study area and can also be used to simulate the impacts of tunnel drainage.

4 Tunnel Impact Evaluation

4.1 Tunnel Drainage Scenarios

According to the tunnel design, the construction period of the tunnel is five years. The predicting period of the simulation ranged from 2016 to 2045. The water quantity of tunnel drainage during the construction period is estimated using Eq. (1), and that after the construction is calculated using the equation described by Yang et al. [5]:

$$Q = \frac{4\mathrm{pmLK}(H - r)}{\ln(2(H - r)/r)} \tag{1}$$

where,

K is the hydraulic conductivity (m/d),
H is the vertical distance of the tunnel below the water level (m),
r is the radius of the tunnel (m),
L is the distance from the tunnel face to secondary lining (m),
m is a conversion coefficient, which usually equals to 0.86.

4.2 The Impacts on Groundwater Level

Figure 2 shows the variation of groundwater level during the construction period. In the initial period of construction, the discharge amount is small and has little effects on the groundwater flow system. After six months, with the increase of water drainage amount, the groundwater flow pattern begins to change, and two groundwater drawdown funnels were formed in the area with high specific yield. At DK629 + 900, the groundwater level starts to increase due to the reducing of water drainage amount; however, the groundwater drawdown area keeps expanding. After 12 months, the two groundwater drawdown funnels expand to one funnel. As the lag of groundwater system response, the groundwater drawdown area keeps expanding until one year after the construction completion. The maximum drawdown area covers 23.95 km^2 (Fig. 4). Groundwater level was observed to increase rapidly after strong drainage; and about one year later, groundwater flow pattern recovered to a state similar to the initial natural state.

The groundwater level generally decreases with the increase of the distance from the center of the drawdown funnel. The largest groundwater drawdown depth is

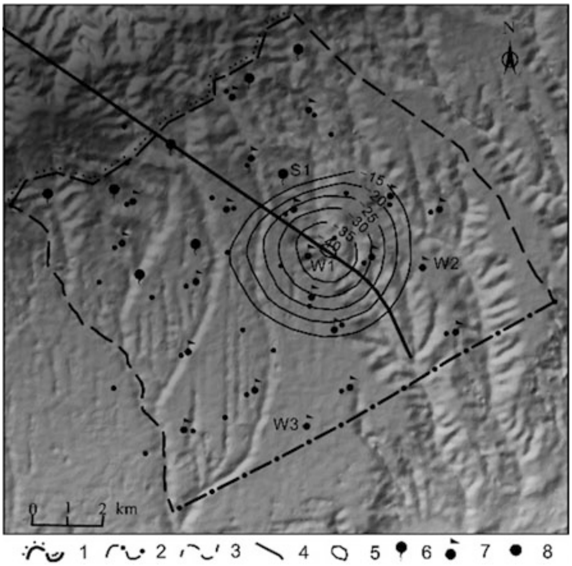

Fig. 4 The maximum impact range of groundwater funnel. 1-Given flux boundary, 2-Given head boundary, 3-General head boundary, 4-Tunnel, 5-Contours of drawdown depth (m), 6-Spring, 7-Well, 8-Village

175 m in the sixth month, and the maximum radius of the drawdown funnel reached 400 m in the twelfth month. Groundwater level fluctuation shows an increasing trend and has a short recovery time in the high specific yield area. Meanwhile, the groundwater level drawdown and the recovery time have little negative effects on the private wells.

4.3 The Impacts on Springs and Groundwater Storage Resource

There are two kinds of springs distributed in the study area, one is the erosion springs located in the loess area, and the other is the overflow springs in the mountainous area. Most of the springs are distributed away from the area of high specific yield; the discharge amount of the springs is less affected by the tunnel drainage. Only one erosion spring (S1) located in the east of DK 627 + 500 is close to the area of high specific yield and is strongly affected by the tunnel drainage (Fig. 5). The initial discharge of S1 is 841 m^3/d and maximally decreases to 629 m^3/d during the tunnel drainage, which is only 75% of the initial discharge. After 3.5 years, with the decrease of the tunnel drainage amount, the spring discharge gradually recovers to 90%.

Surface water reservoirs are distributed in the study area, which have weak hydrological connection with groundwater due to the existence of the aquitards. Under current conditions, the recharge amount is 4320 m^3/d; while, half a year after the construction, the recharge amount is 3866 m^3/d, which is the 89% of the initial

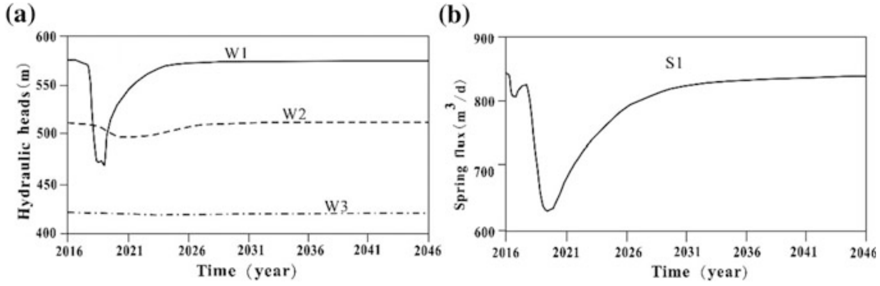

Fig. 5 **a** Process curve of water level fluctuation for typical observation wells, **b** Process curves of spring flux fluctuation

amount. The recharge amount can recover to 4093 m^3/d after 5.5 years, accounting 95% of the initial amount. Furthermore, the tunnel drainage has temporal influences on the reservoir resource and can quickly recover after the construction. As a result, the tunnel construction has little effects on the groundwater system in respect to the long term.

5 Summary

In this study, the impacts of mountainous tunnel drainage on groundwater were quantitatively assessed using numerical modelling approach. The results indicate that numerical simulation is a useful and effective tool to identify potential impacts on the groundwater environment. The tunnel drainage can result in fluctuations of groundwater level, and forming groundwater drawdown funnels. However, the serious drawdown area is no more than 400 m away from the tunnel and can be recovered rapidly after the tunnel construction. Tunnel drainage also reduces the discharge amount of springs and the aquifer reservoir quantity; however, the influences can be rapidly eliminated after the strong drainage. The private wells close to the tunnel are affected by tunnel drainage, but the influence is limited and temporal. In general, mountainous tunnel drainage would have negative influences on the groundwater environment as well as human life, but these influences can be eliminated rapidly after the tunnel construction due to the rich rainfall in the mountainous area.

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