Comprehensive Evaluation of Hydrogeological Impact of Tunnel Construction in Karst Aquifers by 3D Numerical Simulations and Water Balance Models

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Abstract. Underground engineering activities such as tunnelling are commonly involved in large-scale hydraulic and hydropower projects. In karst regions, tunnel engineering often encounters geological disasters such as water inrush and ground collapse. Water discharge during tunnel construction can also strongly disturb the karst groundwater systems. The above issues require a comprehensive evaluation of the hydrogeological impact of tunnel engineering. In this study, we adopted both a 3D numerical approach based on coupled discrete-continuum models and a modified lumped-parameter water balance model to comprehensively evaluate the hydrogeological impact of tunnel engineering during implementation of the Jiayan Water Diversion Project in Guizhou Province. In the numerical approach, a high-resolution 3D model was built to quantitatively evaluate the spatial and temporal characteristics of the tunnel construction impact on a karst groundwater system. It was shown that during construction, the groundwater drainage through the tunnels accounted for about 11\% of the total groundwater discharge in the studied area. The total discharge through karst conduits decreases by about 30\% in response to the tunnel construction. Meanwhile, the lumped-parameter water balance model provided an avenue for fast evaluation the impact of tunnel construction on the discharge from the aquifer system. The discharge through the spring and tunnels evaluated by water balance model are in good agreement with the results of the numerical model. On a whole, our work demonstrates the use of different modelling approaches to study karst groundwater flow affected by tunnel engineering that can be of values for different stages of an engineering project.

1. Introduction
Karst aquifers are widely distributed in the world’s land area, and are an important source of drinking water [1-2]. In China, karst area covers up to one third of the country’s land area [3]. The tunnel construction projects in southwest China where karst landforms are widely distributed are gradually increasing [4]. The influence of tunnel engineering on karst water resources has attracted more and more attention. The focus has gradually shifted from the geological disasters associated with tunnel engineering, such as ground collapse [4] and water inrush [5-6], to the ecological impact of tunnel construction on karst aquifer [7]. The excavation of tunnels in karst aquifer will bring a continuous decrease in groundwater level that will lead to, for example, decrease in the water level of karst springs [8], increasing the burden of access to drinking water [9], decrease in soil moisture content [10], and endangerment of surface vegetation [11].
Predicting groundwater flow in karst aquifers is challenging due to the hydrogeological heterogeneity and complex flow characteristics [12]. A series of hydrological models have been applied to meet the challenges of groundwater analysis in karst aquifers, mainly including distributed models and lumped models. The distributed models describe the groundwater flow in aquifers by solving the partial differential equation (PDE) of groundwater flow (e.g., [13-16]). Compared with the traditional numerical approach including the equivalent porous medium (EPM) model and the double continuum (DC) model, the coupled discrete-continuum (CDC) model can better reflect the hydrogeological heterogeneity in karst aquifer [17-18]. The lumped models establish linear or nonlinear relationships between storage and discharge among the generalized physical processes rather than modelling spatial variability explicitly. It is suitable for groundwater simulation with limited observed data or description of hydrogeological characteristics, because it only needs the recharge and discharge data of the groundwater in the aquifer [19-20].

This study aims to quantitatively assess the hydrogeological impact of a karst aquifer caused by tunnel engineering. We built a three-dimensional CDC model considering the detailed schedules of tunnel construction and a lumped water balance model to analyse the hydrological process and the impact of tunnel engineering on groundwater.

2. Site characterization

2.1. General description

The Jiayan Water Diversion Project (JWDP) is a large-scale project located in Guizhou Province, southwest China, where karst landscapes are the dominant components of the land area [14]. The JWDP consists of main tunnels and branch tunnels with a total length of 648.19 km. In this work, two tunnels are considered in the study site (with a total area of about 373 km²): the Maochang tunnel (MCT) with a length of 15.696 km and the Shuidaqiao tunnel (SDT) with a length of 20.365 km. The elevations of the two tunnels are about 1300 m. The ground surface altitudes range from 1050 to 2300 m a.s.l., sloping from northwest to southeast. The average annual temperature is 11.8 °C and the mean annual rainfall is 1120.8 mm.

2.2. Geologic settings

In the study area, the predominant rocks are limestone and dolomite, with a small proportion of insoluble rocks including siltstone, mudstone and sandstone. The hydraulic conductivity of the aquifer is mainly on the order of $10^{-7}$ m/s and $10^{-6}$ m/s according to the pumping test and the statistical distribution in Southwest China [21]. There are 6 permeable faults in the study area, the hydraulic of which is set as $5 \times 10^{-5}$ m/s, roughly based on geological information according to the hydrogeological survey.

As shown in figure 1, the study area is bounded by constant head boundaries (the Liuchong river and the Baifu river), no-flow boundaries (the northern ridgeline and the Machang impermeable faults) and recharge boundary (the surface topography).

There are six underground rivers in the study area (figure 1). According to [22], the study can be divided into four relatively independent hydrogeological units (HUs), namely, Maochang, Xiaotianba, Yinatianba and Shuchang from west to east. The Dapo, Goudaoyan and Maluodong underground rivers are distributed in Maochang HU, and the Xiaotianba underground river is located in Xiaotianba HU. These four underground rivers flow from north to south, discharging to the Liuchong River. The Yinatianba and Shuahing underground river is developed in the Yinatianba and Shuahing HU, respectively, flowing from west to east and discharging to the Baifu River.

3. Methods

3.1. Numerical simulation method

The numerical simulation adopts the CDC method which couples flow in conduits as discrete elements to groundwater flows in the continuum matrix. The finite difference groundwater simulator MODFLOW-2005 [23] is used to solve the PDE of groundwater flow:
\[ \nabla \cdot (K \nabla H) \pm W = S_s \cdot \partial H / \partial t \]  

where \( K \) is the hydraulic conductivity tensor; \( H \) is the hydraulic head; \( S_s \) is specific storage; \( W \) is a source/sink term including recharge and pumping.

The laminar flow and turbulent flow in conduits (including tunnels and underground rivers) are respectively described as:

\[ Q_{\text{lam}} = -\pi d^4 \rho g \Delta H \left( \frac{128 \mu \pi \Delta t}{\rho d^3} \right)^{-1} \]  

\[ Q_{\text{turb}} = -\left( |\Delta H| g d^3 \pi^2 \left( 2 \Delta l / \pi \right)^{1/2} \right) \log \left( k_c / 3.71d + 2.51v \left( 2 |\Delta H| g d^3 / \Delta l / \pi \right)^{1/2} \right) \Delta H / |\Delta H| \]  

where \( d \) is the diameter of conduit, \( \rho \) is the density of groundwater, \( \mu \) is the dynamic viscosity; \( v \) is the kinematic viscosity, \( \tau \) is the tortuosity of conduit, \( k_c \) is the average protrusion height of the conduit wall, and \( \Delta H \) is the head loss along length of \( \Delta l \). Every discrete conduit element shall be balanced between inflow, outflow, linear volumetric exchange between the conduit and the continuum, direct recharge and change in storage of conduit. More details can be found in [24].

### 3.2. Numerical model calibration and condition

The groundwater level data collected from 21 observation wells in the study area were used for steady-state model calibration. The calibrated parameters included the hydraulic conductivities and effective recharge coefficients. According to the geological information, the study area was divided into 6 strata groups (from HC1 to HC6) shown in figure 1. The calibrated hydraulic conductivities of these groups were, respectively, \( 2.66 \times 10^7 \) m/s, \( 1.04 \times 10^6 \) m/s, \( 9.72 \times 10^5 \) m/s, \( 8.91 \times 10^7 \) m/s, \( 5.67 \times 10^7 \) m/s and \( 8.79 \times 10^7 \) m/s. Moreover, the study area was divided into three rainfall infiltration coefficient groups according to the surface topography. The calibrated effective infiltration coefficient varied from 10% to 25%. As shown in figure 2, most of errors between simulated groundwater levels based on calibrated parameters and observed data were less than 40 m.

![Figure 1. Surface topography, boundary conditions of the model and the hydraulic conductivity zones of the study area according to the lithology of the stratum.](image)

Based on the hydrogeological parameters inversed by calibration and the initial distribution of groundwater level (see figure 2), transient simulations during the construction period (lasts from January 2016 to Dec 2019) were carried out to investigate the impact of tunnel construction on the groundwater in the karst aquifer. A more detailed description of the method for considering the excavation and lining progress of the tunnel can be found in [25].

### 3.3. Lumped-parameter model

A modified lumped parameter model consisting of four flow compartments was used to evaluate the relationship between groundwater recharge and discharge of the independent hydrogeological unit in the karst system. There is an underground river (i.e., Shuchang) in the Shuchang HU that discharges to the Baifu River at the Shuchang spring at elevation of 1160 m, with a length of ~5.9 km and a mean slope of ~4%. According to [22], the discharge of spring and tunnel can be well estimated by the lumped parameter model in the Shuchang hydrogeological unit of the JWDP. Due to the limitations in data collection, the obtained parameters calibrated by the Shuchang hydrogeological unit was used to evaluate the whole study area and to estimate the spring discharge and tunnel discharge.
4. Results

4.1. Three-dimensional groundwater simulation results

The initial distribution of groundwater is shown as figure 2. The initial groundwater level was 0~250 m above the tunnel elevation in most areas across the tunnel. In general, groundwater flows from the north to the southwest (the Liuchong river) and the east (the Baifu river). Under the influence of regional rainfall and the progression of tunnel construction, the water influx to tunnel changed constantly during the construction period. The simulated water influx to tunnel was generally consistent with the observed data. According to the simulated data, the water influx to MCT and SDT reached a maximum (~250 L/s and ~400 L/s, respectively) in around Aug 2017 to Sep 2018 due to the combined effect of rainfall, excavation and lining schedule. In the modelling, the excavated and lined length of the tunnel were updated every three months. Thus, the simulated water inflows to the tunnels showed step-like changes. The response of tunnel influx to rainfall was less obvious than that to the construction schedule.
Figure 3. The water influx to tunnel during the construction period.

A significant drawdown of groundwater around the tunnel was caused by the concentrated drainage effect of the tunnel. The maximum drawdown along the tunnel during construction process (in Sept 2018) even exceeded 90 m at some location. This was mainly caused by the tunnel excavation. The groundwater level had recovered significantly at some location (i.e., 3-6 km in SDT) on Sept 2019. This suggests that the tunnel lining played a major part on the recovery of groundwater levels along the tunnel axis.

The long-term drainage effect of the tunnel results in an obvious decrease in the groundwater storage during the construction period in the study area. According to the groundwater flow budget, the total discharge to karst conduits (from $6.89 \times 10^7$ m$^3$ without tunnel to $5.08 \times 10^7$ m$^3$ with tunnel) caused by the decrease of groundwater level.

The total discharge through tunnel ($5.3 \times 10^7$ m$^3$) accounts for a considerable part of the total discharge in study area (~11%). The net loss of the aquifer’s groundwater storage reaches about $4.5 \times 10^7$ m$^3$ due to tunnel construction in the study area.

4.2. Lumped-parameter model results

Based on the description of recharge and discharge conditions in the numerical model, the spring and tunnel (MCT and SDT) discharge of JWDP region was evaluated by the modified lumped parameter model. The daily discharge through the spring and tunnels with the 95% confidence interval is shown in figure 5. The average discharge of spring in JWDP region was about 2.99 m$^3$/s, and the average value of tunnel discharge was about 0.67 m$^3$/s during 2018. Meanwhile, the tunnel discharge was close to the mean simulated value of 0.58 m$^3$/s obtained by the numerical model during 2018. Therefore, the lumped parameter model can be used to rapidly predict the daily discharge of spring and tunnel in short term when the rainfall data is available.
5. Conclusion
Simulation of groundwater flow in a karst aquifer with a deep buried, large-scale tunnel system is particularly challenging due to complex hydrogeological characteristics. Based on site characterization, groundwater observations and discharge data, the CDC numerical approach and lumped-parameter hydrological model were utilized to comprehensively evaluate the hydrogeological impact of tunnel engineering during implementation of the JWDP in Guizhou Province. In the numerical approach, a 3D high-resolution numerical model was built for the karst aquifer to simulate the dynamic impact of tunnel engineering on karst aquifer with tunnel lengths and hydraulic properties given as time-evolving parameters according to the construction schedule. The numerical results accurately reproduced the time-series of tunnel discharges. During the construction period, the discharge of groundwater through the tunnels accounts for a considerable part of the total discharge (~11%), which results in a great lowering of the groundwater level with the drawdown even exceeding 90 m at certain locations. Meanwhile, the lumped-parameter approach provided an avenue for fast evaluation the impact of tunnel construction on the discharge from the aquifer system. The discharge through the spring and tunnels was efficiently estimated by the lumped model in the study area. The average discharge of spring and tunnel in 2018 was about 2.99 m$^3$/s and 0.67 m$^3$/s, respectively, in good agreement with the results obtained by the numerical model. Both the lumped parameter water balance modelling method and the CDC modelling method are valuable for tunnel project at different stages. The former can be used for feasibility study and preliminary design stage, for rapid and regional scale evaluation of hydrogeological conditions, and the later can be used to optimize the construction process to reduce the impact on hydrogeology and to ensure the safety of construction.

6. References
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