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Research Article

Evaluation of the Influence Caused by Tunnel Construction on Groundwater Environment: A Case Study of Tongluoshan Tunnel, China

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Problems related to water inflow during tunnel construction are challenging to designers, workers, and management departments, as they can threaten tunneling project from safety, time, and economic aspects. Identifying the impacts on groundwater environment resulting from tunnel drainage and making a correct assessment before tunnel construction is essential to better understand troubles that would be encountered during tunnel excavation and helpful to adopt appropriate countermeasures to minimize the influences. This study presents an indicator system and quantifies each indicator of Tongluoshan tunnel, which is located in southwest China with a length of 5.2 km and mainly passes through carbonate rocks and sandstones, based on field investigation and related technological reports. Then, an evaluation is made using fuzzy comprehensive assessment method, with a result showing that it had influenced the local groundwater environment at a moderate degree. Information fed back from environmental investigation and hydrologic monitoring carried out during the main construction period proves the evaluation, as the flow of some springs and streams located beside the tunnel route was found experiencing an apparent decline.

1. Introduction

Nowadays, more and more tunnels are constructed for the reason that efficient transport strongly relies on road and railway tunnel, both in long-distance traffic and in metropolitan areas [1, 2]. However, when a tunnel interferes with groundwater in complex geological media, especially in carbonate karstic rocks, serious problems can arise during the excavation because of groundwater inflow, which is known as one of the most common but challenging problems faced by tunnel designers and constructors, leading to unsafe conditions, high construction costs, and delays, not to mention the risk to life and damage to property [1, 3–7]. Yuanliangshan tunnel on Chongqing-Huaihua railway in China came across three large filled caves at Maoba syncline carbonate strata, and a volume of approximately 4200 m^3 of clay erupted within 30 seconds in one cave of them, causing casualties and severe damage to the equipment in tunnel [8]. During the construction of Pinglin tunnel in Taiwan, the major difficulties encountered are caused by sudden high-pressure groundwater inflow, with a yield of approximately 180 L/s in the pilot tunnel as an example, leading to the TBM being trapped and damaged and construction progress being greatly impacted [9]. Due to fluid drainage and pore pressure changes following tunnel construction, vertical settlements with magnitudes reaching 12 cm were measured in fractured crystalline rock several hundred meters above the Gotthard highway tunnel in central Switzerland [10]. A series of hydrogeological problems with geotechnical and environmental impacts, causing spring discharges drying up and leading to a public protest, occurred during the construction of one of the high-speed railway tunnels between Malaga and Córdoba in south Spain [11]. Similar phenomena can also be observed during the drilling of the Firenzuola tunnel in Italy, water inrushes resulting in water table dropping below the level of the valleys and the gaining streams being transformed into losing streams or running completely dry, as did many springs, leading to severe damage to the aquatic fauna and other elements of the ecosystem [12].

Historically, groundwater studies associated with the design and construction of large underground structures have focused primarily on methods for control of groundwater inflows during excavation and for keeping the completed structure free of water. However, within the last several decades, the impacts of such activities on environment have become a major consideration. Though the impacts on groundwater resources of an area by underground excavation may be minimized by such planned constraints as preexcavation grouting and installation of an impermeable lining of the final excavation, such measures may not be efficient for avoiding claims of environmental impacts, particularly in areas of existing water shortages and/or marginal supplies [13]. As any groundwater drawdown alters the natural hydrogeological flow system and can consequently impact groundwater-dependent vegetation, surface streams, lakes, wetlands, and associated aquatic ecosystems, as well as springs and wells, the wise approach is to assess the potential hydrological and ecological impact of a tunnel before building it and take appropriate measures to minimize the impact [12].

As mentioned above, groundwater inflow is one of the most complicated problems which can pose a serious risk and induce impacts on groundwater environment during the tunnel excavation. Accordingly, a number of measures must be adopted to minimize these effects. Appropriate measures can only be taken once the impacts are correctly identified, but it is a difficult task to obtain the correct identification [14]. Fortunately, some relative researches are trying to do this. For instance, a quantitative evaluation of hydrogeological impacts produced by a tunnel of 3 m in diameter and over 7 km in length in the surroundings of the city of Ferrol, NW of Spain, was assessed by means of calculating the hydrogeological behaviors before and after the tunnel excavation using water balance models, and then a comparison was made to allow for the quantitative evaluation of the changes in groundwater flow and the variation in the amount of water corresponding to each component of the model [14]; Tracer tests using uranine and sulforhodamine G and hydrological observations consisting of springs and streams were adopted to evaluate the effects of tunnel drainage on groundwater and surface waters in the Northern Apennines, Italy [12]; Yang et al. [15] utilized a numerical method and MODFLOW codes to simulate groundwater flow pattern in the tunnel area and determine the impact of tunneling excavation on hydrogeological environment in a regional area around the tunnel and a local hot springs area, at the "Tseng-Wen Reservoir Transbasin Diversion Project," in Taiwan.

Since the hydrologic and geologic system are very rare to be completely understood due to their complexity and heterogeneity, there are many difficulties and uncertainties existing in identifying the impacts caused by tunnel excavation on groundwater environment. Compared to problems, such as time delay and increase in costs, and losses to ecosystem and society, induced by drainage from tunnel, it is very essential to make an assessment of the negative effects caused by tunnel excavation prior to constructing it. Despite the fact that some efforts have been made to try achieving this goal, more works should be done to enrich the related researches.

This study presented in this paper focuses on evaluating the influence resulting from tunnel excavation on groundwater environment, by means of employing an indicator system proposed by Liu [16]. The procedure presented in this paper is applied to a case study of the Tongluoshan tunnel constructed in southwest China, where the karstification is well developed [17]. In order to completely understand the impacts caused by the excavation of Tongluoshan tunnel, some representative hydrological points and drainage from tunnel as well as precipitation in the tunnel area have been observed during most of the construction period.

2. Methodology

2.1. Indicator System for Assessment of the Influence Caused by Tunnel Construction. Water inflow is known as one of the most challenging problems during the tunnel construction, and many other hydrological and geological troubles such as regional water table drawdown, surface subsidence, and wells and springs drying up are induced by it. In order to assess the impacts caused by tunnel excavation on groundwater environment, indicators that closely related to water inflow into tunnel should be firstly taken into consideration. As both mining and tunneling are subsurface activities encountering the risk and damage produced by water inflow [1, 18], the same attention should be paid to the factors controlling water inrush to mine.

As concluded by Liu [16], the factors affecting water inflow during tunnel excavation can be classified into three categories including physical geography, geology and hydrogeology, and tunnel engineering. Each category can also be subdivided into several indicators which extremely explain how this category impacts tunnel inflow. In the category of physical geography, seven indicators such as average annual rainfall, average annual evaporation, area of catchment zone, coefficient of rainfall infiltration, relationship between the tunnel and geomorphology, capacities of reservoirs and lakes on the ground, and flow of surface rivers are included. It is necessary to note that catchment area does not always refer to the whole area of the hydrogeological unit that tunnel is located in but means a zone which collects water from precipitation and contributes to water inflow. Another source of water inflow is surface water, which should not be ignored because of its powerful ability to supply tunnel with abundant water. All the surface water contributing to water inflow should be taken into consideration when quantifying the indicators including capacities of reservoirs and lakes on the ground and flow of surface rivers. The category of geology and hydrogeology is composed of seven indicators too, which are carbonate rocks exposure ratio, water yield properties of the aquifers, water pressure on the tunnel, development of folds, development of fracture zones, formation lithology, and location of tunnel in horizontal and vertical hydrodynamic zoning of groundwater. The last category, tunnel engineering, consists of length of tunnel, area of disturbed range, construction method, burial depth of tunnel, and measures for prevention of groundwater flowing into tunnel. It is worth noting that water inflow does not always increase or decrease over burial depth of tunnel, but a special range of depths may be suitable for groundwater flowing toward tunnel.

The structure of the indicator system constructed by Liu [16] aiming at assessing the negative effects caused by tunnel excavation can be seen in Table 1.

2.2. Fuzzy Comprehensive Assessment. The concept of fuzzy sets describing imprecision or vagueness was introduced by Zadeh [19]. Fuzzy logic where an element can belong partially to several subsets may be regarded as an extension of classical Boolean logic where belonging or not to a set is mutually exclusive. It simplifies the process of taking decisions by simulating the way of reasoning of a human expert in environments characterized by uncertainty and imprecision. Fuzzy evaluation methods process all the components according to predetermined weights and decrease the fuzziness by using the membership function; therefore, the sensitivity of fuzzy evaluation is quite high compared to other index evaluation techniques [20–22].

The following procedure describes fuzzy comprehensive assessment [21].

(a) Selection of Factor Set U. Consider

$$U = \{u_i\}, \quad i = 1, 2, \ldots, n, \tag{1}$$

where n is the number of selected evaluation factors. In this study, 19 indicators listed in Table 1 are selected to build the factor set; in other words, $n = 19$.

(b) Construction of Evaluation Criteria Set V. Consider

$$V = \{v_j\}, \quad j = 1, 2, \ldots, m, \tag{2}$$

where m is the number of evaluation criteria categories and v_j is the threshold of the jth criteria category. In the present study, outputs of the assessment are classified into five grades shown in Table 2, along with corresponding evaluation criteria of each indicator. From grade 1 to grade 5, the extent of groundwater environment influenced by tunnel construction ranges from very weak to very strong.

(c) Establishment of Membership Functions. In fuzzy logic, the set A is defined in terms of its membership function by

$$A = \{(f_A(x)),\ x \in X,\ f_A(x) \in [0, 1]\}, \tag{3}$$

where X is a domain, with a generic element of X denoted by x, f_A is the membership function of the set A, which maps the domain X onto the interval $[0\ \ 1]$, and $f_A(x)$ represents the degree that x belongs to set A. x is a full member of A when $f_A(x) = 1$, not member of A when $f_A(x) = 0$, and a partial member of A when $f_A(x) = (0, 1)$.

The membership function of each factor to the assessment criteria at each grade can be described quantitatively by a set of formulae as follows (4) (Note: if a big value represents a small contribution to water inrush and problems induced by it, then the direction of the inequality in the conditions should be reversed):

$$f_{ij}(x_i) = \begin{cases} 0 & x_i > v_{i(j+1)}, \\ \dfrac{(v_{i(j+1)} - x_i)}{(v_{i(k+1)} - v_{ik})} & v_{ij} \le x_i \le v_{i(j+1)}, \quad j = 1, \\ 1 & x_i < v_{ij}, \end{cases}$$

$$f_{ij}(x_i) = \begin{cases} 0 & x_i > v_{i(j+1)},\ x_i < v_{i(j-1)}, \\ \dfrac{(x_i - v_{i(j-1)})}{(v_{ij} - v_{i(j-1)})} & v_{i(j-1)} \le x_i \le v_{ij}, \\ \dfrac{(v_{i(j+1)} - x_i)}{(v_{i(j+1)} - v_{ij})} & v_{ij} \le x_i \le v_{i(j+1)}, \end{cases} \quad j = 2, 3, 4, \tag{4}$$

$$f_{ij}(x_i) = \begin{cases} 0 & x_i < v_{i(j-1)}, \\ \dfrac{(x_i - v_{i(j-1)})}{(v_{ij} - v_{i(j-1)})} & v_{i(j-1)} \le x_i \le v_{ij}, \quad j = 5, \\ 1 & x_i > v_{ij}, \end{cases}$$

where i is the number of evaluation factors ($i = 1, 2, 3$), j is the number of assessment criteria levels ($j = 1, 2, 3, 4, 5$), x_i is the actual value of evaluation factor i, v_{ij}, $v_{i(j-1)}$, $v_{i(j+1)}$ is the assessment criteria threshold of the ith assessment factor at level j, $j - 1$, $j + 1$, respectively, and $f_{ij}(x_i)$ is the membership degree of assessment factor i at level j.

(d) Calculation of Fuzzy Relation Matrix R. Substituting the data of each indicator and the gradation criteria into the membership function listed above, the fuzzy matrix R can be expressed as

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}, \tag{5}$$

where r_{ij} ($i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, m$) is the membership degree of the ith assessment parameter at the jth level.

(e) Determination of Weight Set W. Consider

$$W = \{w_i\}, \quad i = 1, 2, \ldots, n, \tag{6}$$

where n is the number of selected evaluation factors and w_i is the weight of ith factor indicating the relative importance.

Determination of the relative weight of each indicator is important for making an appropriate assessment. 10 experts and professors engaged in hydrological and environmental studies coming from home and broad were invited to identify the relative importance of each category and indicator according to their knowledge and experience. After obtaining

Table 1: Indicator system for assessment of the negative effects caused by tunnel excavation on groundwater environment [16].

Objective layer	Rule layer	Indicator layer	Definition and explanation
[A] assessment of the negative effects caused by tunnel excavation on groundwater environment	[B_1] physical geography	[C_{11}] average annual rainfall (mm)	Average value of annual precipitation in the previous five to ten years
		[C_{12}] average annual evaporation (mm)	Average value of annual evaporation in the previous five to ten years
		[C_{13}] area of catchment zone (km^2)	Area of the catchment zone that collects water contributing to water inrush into tunnel
		[C_{14}] coefficient of rainfall infiltration	The proportion of atmospheric precipitation contributing to groundwater recharge
		[C_{15}] spatial relationship between the tunnel and geomorphology	Spatial relationships between tunnel and geomorphology on cross and longitudinal section
		[C_{16}] capacities of reservoirs and lakes on the ground (m^3)	Capacities of reservoirs and lakes, located on the ground, which may become water sources of tunnel inflow
		[C_{17}] flow of surface rivers (m^3/s)	Flow of surface rivers which may supply tunnel with water
	[B_2] geology and hydrogeology	[C_{21}] carbonate rocks exposure ratio (%)	Areal ratio of outcropping carbonate rocks to the catchment zone contributing to water inflow in the plane
		[C_{22}] water yield property of aquifers	Water yield property of aquifers that may provide tunnel with water
		[C_{23}] water pressure on the tunnel (Mpa)	Hydrostatic pressure on tunnel
		[C_{24}] development of folds	Characteristics and scale of folds, as well as the development of water passages formed during folds formation
		[C_{25}] development of fracture zones	Development of fracture zones which may become water channels primarily including faults-fracture zone, joints concentrated zone, and contact zone of different lithology
		[C_{26}] formation lithology	Strata lithologic and its proportion
		[C_{27}] location of tunnel in horizontal and vertical hydrodynamic zoning of groundwater	Location of tunnel in horizontal hydrodynamic zone of groundwater including recharge zone, runoff zone and discharge zone, and in vertical hydrodynamic zone of groundwater, consisting of epikarst zone, aeration zone, seasonal fluctuation zone, shallow saturation zone, stressful saturation zone and deep circulation zone
	[B_3] tunnel engineers	[C_{31}] length of tunnel (km)	Length along the tunnel axis
		[C_{32}] area of disturbed range (m^2)	Area of the zone that may be disturbed by tunnel excavation
		[C_{33}] construction method	Methods used to excavate tunnel, mainly including drilling and blasting method, New Austrian Tunneling Method, and tunnel boring machine method
		[C_{34}] burial depth of tunnel (m)	Vertical distance from ceiling of the tunnel to ground surface
		[C_{35}] measures for prevention of groundwater flowing into tunnel	Ideas and technologies adopted to prevent and treat groundwater flowing into tunnel

Table 2: Criteria for assessment of the negative effects caused by tunnel excavation on groundwater environment [16].

Indicator	Criteria: Very weak	Weak	Moderate	Strong	Very strong
[C_{11}] average annual rainfall (mm)	<600	600~800	800~1000	1000~1600	>1600
[C_{12}] average annual evaporation (mm)	>800	600~800	500~600	400~500	<400
[C_{13}] area of catchment zone (km^2)	<5	5~10	10~30	30~50	>50
[C_{14}] coefficient of rainfall infiltration	<0.05	0.05~0.15	0.15~0.30	0.30~0.50	>0.50
[C_{15}] spatial relationship between the tunnel and geomorphology	Other (such as flat, protruding)	Flat and basin-shaped	Angular space and river crossing	Side below the valley and river crossing	Right below the valley and river crossing
[C_{16}] capacities of reservoirs and lakes on the ground (m^3)	<1	1~10	10~50	50~300	>300
[C_{17}] flow of surface rivers (m^3/s)	<0.1	0.1~0.5	0.5~2.0	2.0~10.0	>10.0
[C_{21}] carbonate rocks exposure ratio (%)	<30	30~50	50~70	70~90	>90
[C_{22}] water yield property of aquifers	<5	5~10	10~15	15~20	>20
[C_{23}] water pressure on the tunnel (Mpa)	<0.5	0.5~1.0	1.0~3.0	3.0~5.0	>5.0
[C_{24}] development of folds	No folds	Folds with undeveloped fissure	Folds with moderately developed fissure	Folds with developed fissure	Folds with developed faults
[C_{25}] development of fracture zones	Rarely developed	Poorly developed	Moderately developed	Developed	Well developed
[C_{26}] formation lithology	Mudstone, shale, or clay	Sandstone or fine sandstone	Granite or igneous rock	Metamorphic rock	Soluble rocks including limestone, dolomite, and so forth
[C_{27}] location of tunnel in horizontal and vertical hydrodynamic zoning of groundwater	Recharge area in horizontal and unsaturated zone in vertical zoning	Recharge area in horizontal and seasonal fluctuation zone in vertical zoning	Runoff area in horizontal and shallow saturation zone or deep circulation zone in vertical zoning	Runoff area in horizontal and stressful saturation zone in vertical zoning	Discharge area in horizontal zoning
[C_{31}] length of tunnel (km)	<1.0	1.0~3.0	3.0~10.0	10.0~30.0	>30.0
[C_{32}] area of disturbed range (m^2)	<50	50~120	120~250	250~350	>350
[C_{33}] construction method	Tunnel boring machine method	New Austrian Tunneling Method	Partial excavation using drilling and blasting method	Benching tunneling using drilling and blasting method	Full face excavation using drilling and blasting method
[C_{34}] burial depth of tunnel (m)	Extremely bad for water inflow	Bad for water inflow	Moderate for water inflow	Good for water inflow	Extremely good for water inflow
[C_{35}] measures for prevention of groundwater flowing into tunnel	Composite lining and pregrouting	Composite lining and exterior waterproof (or postgrouting)	Composite lining	Structural self-waterproof	Drainage

Table 3: Comprehensive weights of the indicators included in the indicator system [16].

Indicator	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{21}	C_{22}	C_{23}
Weight	0.0535	0.0251	0.0387	0.0386	0.0539	0.0419	0.0419	0.0679	0.0705	0.0393
Indicator	C_{24}	C_{25}	C_{26}	C_{27}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	
Weight	0.0617	0.0834	0.0781	0.0681	0.0554	0.0362	0.0477	0.0445	0.0538	

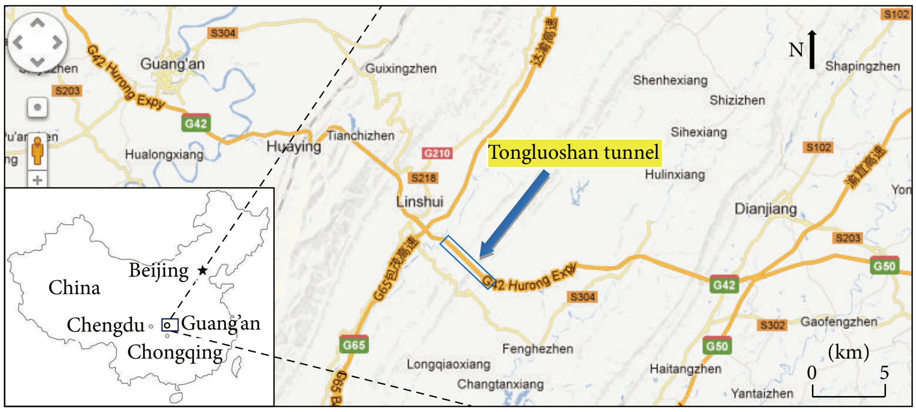

Figure 1: Location map of Tongluoshan tunnel.

the sequence and its score representing the relative importance of each factor, weight set (Table 3) is calculated using G1-rank correlation analysis method proposed by Guo [23].

(f) Fuzzy Matrix Composition and Determination of the Final Evaluation Result. Fuzzy composition evaluation can be performed as follows:

$$E = W * R = (w_1, w_2, \dots, w_n) \begin{bmatrix} r_{11} & \cdots & r_{15} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{n5} \end{bmatrix} = (e_1, e_2, \dots, e_5), \tag{7}$$

where W and R are the weight set and the fuzzy relationship matrix determined above, respectively, and $*$ is a fuzzy composite operator which is very critical to final evaluation results. In this study, average fuzzy composite operator is chosen.

3. Case Study of Tongluoshan Tunnel

3.1. General Description

3.1.1. Project Profile. Tongluoshan tunnel, with a length about 5.2 km, located in Guang'an, Southwest China (Figure 1), is a key project of Dianjiang-Linshui expressway. This project consists of two parallel tunnels, between which the distance is 30 m (from the adjacent walls). The thickest overburden of Tongluoshan tunnel is approximately 280 m, while the minimum value is less than 40 m. In order to save time, excavations were executed simultaneously from the northwest portal and southeast portal to the center during 2005 to 2008.

3.1.2. Climatic and Hydrological Features of the Tunnel Area. The tunnel area belongs to subtropics monsoon climate region, where precipitation is abundant but distributing unevenly throughout the year with the majority (70%) falling from May to September. Annual precipitation in the tunnel area oscillates between 836.6 mm and 1529.8 mm with an average of 1215.5 mm. Mean annual temperature in the tunnel area is 16.9°C, with the highest and lowest daily temperature 40.4°C and −3.8°C, respectively.

Tongluoshan tunnel is located in the middle of Tongluoshan anticline, where Yulin River and Zhonghe River, belonging to the secondary and first branch of Yangtze River respectively, are the main regional surface water bodies. The major river in the tunnel area is Qingshuixi River, which originates from Jinzhong reservoir northeast of Tongluoshan tunnel and flows approximately 8.8 km along the axis of Tongluoshan anticline and then turns to southeast. After about 2.5 km, it becomes a part of Zhonghe River. As is recorded, the average annual flow rate of Qingshuixi River is about 0.355 m^3/s before tunnel construction.

3.1.3. Geological and Hydrogeological Characteristics of the Tunnel Area. Ground surface elevation ranges from 156 m to 1053 m in a regional scale while the northern part is higher than the southern part which Yangtze River goes through. In the tunnel area, elevation in the valley along the route of Tongluoshan anticline oscillates between 400 m to 550 m, which is much smaller than that in the anticlinal flanks ranging from 600 m to 750 m.

According to the preliminary geological survey undertaken by Sichuan Institute of Coal Field Geological Engineering Exploration and Design [24] and other information about tunnel design, few except a small fault (F_1) and Tongluoshan anticline are the major geological structures developing in

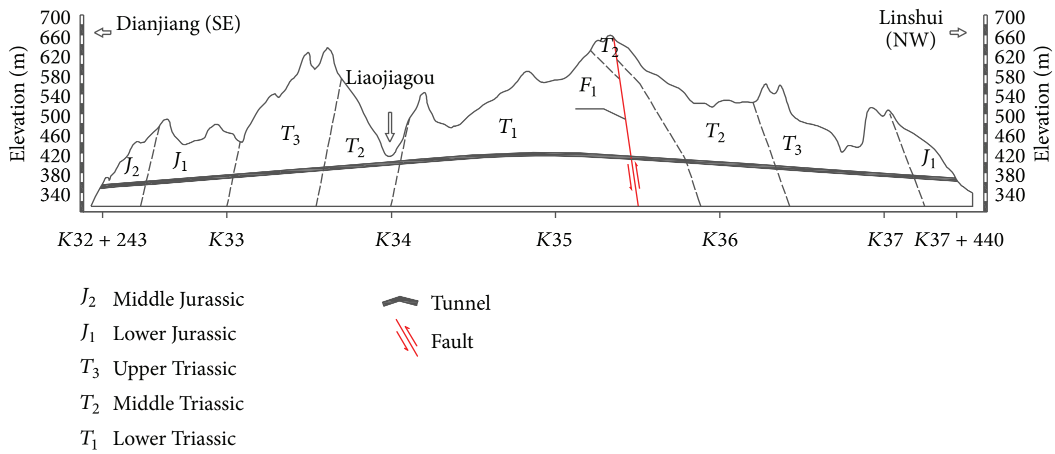

FIGURE 2: Geological profile of Tongluoshan tunnel.

the tunnel area. And the stratigraphic sequence consists of carbonate rocks of lower to middle Triassic (T_2, T_1), coal measure strata of upper Triassic (T_3), mudstone interbedded with siltstone of lower to middle Jurassic (J_2, J_1), and unconsolidated sediments in Quaternary (Q). The geological profile along the route is shown in Figure 2.

Tongluoshan tunnel is located in the southern part of Qingshuixi secondary hydrogeological unit, which is bounded by Yujiayakou watershed in the south, Shengouzigou watershed in the north, Yulin River in the west, and Zhonghe River in the east. This hydrogeological unit has an area about 95 km^2, stretching 11.9 km from the southern boundary to the northern boundary, and 7 to 9 km in the west-east direction. According to the topography, geological structure, water-bearing medium and recharge, runoff, and discharge condition of groundwater in this hydrogeological unit, it can be divided into four aquifer systems, composed of pore water in the unconsolidated formation of Quaternary, pore and fissure water in the clasolite of Jurassic, pore and fissure water in the clasolite of upper Triassic, and carbonate water in the carbonate rocks of lower to middle Triassic. Precipitation is believed to be the primary source of recharge to the aquifers. Groundwater recharge occurs mainly from infiltration of precipitation into outcropping carbonate rocks, including stratum of lower to middle Triassic principally distributed in the core area of Tongluoshan anticline. Controlled by the coal-bearing strata and mudstone interbedded with siltstone located in the anticlinal flanks, karst groundwater generally flows towards the south and mainly discharges in terms of springs along Qingshuixi River, which is viewed as local base level of erosion.

3.2. Fuzzy Comprehensive Evaluation of the Influence Caused by Tunnel Excavation on Groundwater Environment

3.2.1. Quantification of the Indicators. In order to assess the negative effects caused by Tongluoshan tunnel construction on groundwater environment, the value of each indicator included in the indicator system should be previously quantified based on field investigation and technological reports related to the project such as geological survey undertaken by Sichuan Institute of Coal Field Geological Engineering Exploration and Design [24] and so on. As some indicators, for example, lithology of the formation and relation between tunnel and topography and burial depth of tunnel, are unique and of great importance to the evaluation result that may play a vital role in decision making, the work of quantification of the indicators should be done as carefully as it can be, aiming at assessing the influence as accurate as possible. Specific value representing quantification of each indicator is listed in Table 4.

3.2.2. Data Preprocessing. Data preprocessing for comprehensive evaluation is to choose an appropriate membership function which determines the membership of each indicator according to given criteria. In this case study, trapezoidal function and semitrapezoidal function (4) are chosen, because of their advantage in simple processing and smooth linking. It is noted that the standard of an indicator at each level can be described as an interval like $[a, b]$, which may have existed or will be built. And it is reasonable for determining the membership of x as 1.0 when $x = (a+b)/2$, so v_{ij} in the equations (e.g., (4)) may be valued as $(a+b)/2$. If difficulties existing in finding an upper or lower limit of some indicators, $\eta = 3\sim5$ or $\eta = 1/5\sim1/3$ can be multiplied to achieve this goal. After substitution of actual value quantified in Table 4 and criteria listed in Table 2 into the membership function, membership of each indictor at every level (Table 5) can be gotten, which will directly be transferred into a fuzzy matrix R.

3.2.3. Fuzzy Comprehensive Evaluation. When prepared, evaluation set W and fuzzy matrix R can be composed using average fuzzy composite operator according to (7):

$$E = W * R = (w_1, w_2, \ldots, w_{19}) \begin{bmatrix} r_{1,1} & \cdots & r_{1,5} \\ \vdots & \ddots & \vdots \\ r_{19,1} & \cdots & r_{19,5} \end{bmatrix}$$

Table 4: Quantification of each factor included in the indicator system.

Category	Indicator	Value of Tonluoshan tunnel
$[B_1]$ physical geography	$[C_{11}]$ average annual rainfall (mm)	According to rainfall records from local meteorological station, the average annual precipitation is 1215.5 mm in the tunnel area.
	$[C_{12}]$ average annual evaporation (mm)	According to evaporation records from local meteorological station, the average annual evaporation is 959.6 mm in the tunnel area.
	$[C_{13}]$ area of catchment zone (km^2)	Tongluoshan tunnel passes through strata consisting of carbonate rocks of high permeability in the core and clastic rocks of low permeability in the flanks of Tongluoshan anticline. When calculating the catchment zone of tunnel inflow, a region composed of local watershed around the route of tunnel in the flanks and the entire karst valley are included. Total area of the catchment zone of Tongluoshan tunnel then is determined to 38.4 km^2.
	$[C_{14}]$ coefficient of rainfall infiltration	Based on the geological investigation report, infiltration coefficient of rainfall in the outcropping carbonate rocks (T_1 and T_2) reaches 0.55, with 0.20 in the coal measure strata (T_3), while it is only 0.054 in the Jurassic clastic rocks (J_1 and J_2). Due to statistics of outcrop in terms of different lithology, 44% of them are carbonate rocks, while 32% are coal bearing strata, and 24% are clastic rocks.
	$[C_{15}]$ spatial relationship between the tunnel and geomorphology	Length consisting of the section between 32 K + 700 and 34 K + 200 and that between 35 K + 800 and 36 K + 300 is about 2 km, belonging to the type of side below the valley and river crossing, while the rest belongs to other type.
	$[C_{16}]$ capacities of reservoirs and lakes on the ground (m^3)	There are no reservoirs and lakes within 2 km from the tunnel axis except Jinzhong reservoir, which is about 9 km far from the tunnel axis, storing approximately 300 thousand cubic meters. Since karstification is well developed in the tunnel area and Jinzhong reservoir is the origin of Qingshuixi River, it is taken into consideration from a safe point of view.
	$[C_{17}]$ flow of surface rivers (m^3/s)	Qingshuixi River is the main surface river which may have hydraulic connection with the water inflow into tunnel.
$[B_2]$ geology and hydrogeology	$[C_{21}]$ carbonate rocks exposure ratio (%)	As mentioned above, this ratio is about 44% in the tunnel area.
	$[C_{22}]$ water yield property of aquifers	Based on the longitudinal profile of Tongluoshan tunnel, area of rocks with poor water yield property occupies 62.37%, with middle standing 30.14%, while the left (7.5%) is considered as aquifer with very good water yield property.
	$[C_{23}]$ water pressure on the tunnel (Mpa)	Average water pressure on the tunnel is estimated as 1.0 MPa.
	$[C_{24}]$ development of folds	Tongluoshan anticline is the main fold developed in the tunnel area with fractures coming from geological and karstic process.
	$[C_{25}]$ development of fracture zones	Fracture zone passed through by tunnel excavation is found moderately developed.
	$[C_{26}]$ formation lithology	Based on outcrops in the tunnel area, mudstone, shale, and clay stand for 21% and sandstone and siltstone stand for 35%, while carbonate rocks occupy 44%.
	$[C_{27}]$ location of tunnel in horizontal and vertical hydrodynamic zoning of groundwater	From a regional scale, Tongluoshan tunnel is located in runoff area in horizontal and stressful saturation zone in vertical zoning.
$[B_3]$ tunnel engineers	$[C_{31}]$ length of tunnel (km)	About 5.2 km.
	$[C_{32}]$ area of disturbed range (m^2)	About 185 m^2 including two tunnels.
	$[C_{33}]$ construction method	About 80% of the tunnel excavated by full face excavation using drilling and blasting method, while the others adopt benching tunneling using drilling and blasting method.
	$[C_{34}]$ burial depth of tunnel (m)	Burial depth between 100 m and 300 m stands for 50%, while the others have a value less than 100 m. From some statistic data and hydrogeological condition in the tunnel area, moderate level is given.
	$[C_{35}]$ measures for prevention of groundwater flowing into tunnel	Composite lining is the prevailing waterproof used by Tongluoshan tunnel, while 20% of which adopts external pregrouting.

Table 5: Membership of each indictor at every level calculated from quantification of Tongluoshan tunnel and the evaluation criteria.

Indicator	Grades				
	Very weak	Weak	Moderate	Strong	Very strong
[C_{11}] average annual rainfall (mm)	0	0	0.211	0.789	0
[C_{12}] average annual evaporation (mm)	0.288	0.712	0	0	0
[C_{13}] area of catchment zone (km^2)	0	0	0.080	0.920	0
[C_{14}] coefficient of rainfall infiltration	0.158	0.146	0.256	0.330	0.110
[C_{15}] spatial relationship between the tunnel and geomorphology	0.600	0	0	0.400	0
[C_{16}] capacities of reservoirs and lakes on the ground (m^3)	0	0	1.000	0	0
[C_{17}] flow of surface rivers (m^3/s)	0	1.000	0	0	0
[C_{21}] carbonate rocks exposure ratio (%)	0	0.800	0.200	0	0
[C_{22}] water yield property of aquifers	0.624	0	0.301	0	0.075
[C_{23}] water pressure on the tunnel (Mpa)	0	0.800	0.200	0	0
[C_{24}] development of folds	0	0	0	1.000	0
[C_{25}] development of fracture zones	0	0	1.000	0	0
[C_{26}] formation lithology	0.210	0.350	0	0	0.440
[C_{27}] location of tunnel in horizontal and vertical hydrodynamic zoning of groundwater	0	0	0	1.000	0
[C_{31}] length of tunnel (km)	0	0.289	0.711	0	0
[C_{32}] area of disturbed range (m^2)	0	0	1.000	0	0
[C_{33}] construction method	0	0	0	0.200	0.800
[C_{34}] burial depth of tunnel (m)	0	0	1.000	0	0
[C_{35}] measures for prevention of groundwater flowing into tunnel	0.200	0	0.800	0	0

$$= (0.117, 0.195, 0.355, 0.251, 0.082). \tag{8}$$

Maximum membership principle [25, 26] is a simple and widely used principle on the membership degree matrix. The elements in the vector of evaluation result stand for the membership degree to assessing level. According to this principle, it can be determined that the assessment result of Tongluoshan tunnel is moderate, as 0.355 is the maximum member in the evaluation result vector. Meanwhile, another weighted mean method [27] which allocates a relative rating (1, 2, 3, 4, and 5, resp.) to the five levels and uses accelerations composition method to calculate the total value is employed to perform calculations:

$$\begin{aligned} T &= 1\times e_1 + 2\times e_2 + 3\times e_3 + 4\times e_4 + 5\times e_5 \\ &= 1\times 0.117 + 2\times 0.195 + 3\times 0.355 + 4\times 0.251 + 5 \\ &\quad \times 0.082 \\ &= 2.99. \end{aligned} \tag{9}$$

Based on the result calculated by weighted mean method, middle level tends to be accepted because T is very close to 3. Therefore, from arithmetically speaking, moderate grade is recommended as the influence level of Tongluoshan tunnel, indicating that the local groundwater environment might have suffered a medium degree of impact from the tunnel excavation.

Although the indicator system supplying us with a convenient way to evaluate the influence resulted from tunnel construction on groundwater environment, field work such as environmental investigation and hydrological monitoring is important and essential to help judge whether the assessment is appropriate or not. Some details about the procedure and result of environmental investigation and hydrological monitoring carried out in Tongluoshan tunnel area are described in the next section.

3.3. Environmental Investigation and Hydrologic Monitoring. Environmental investigation and hydrologic monitoring in the project area that may be affected was implemented for the early detection of environmental impacts caused by tunnel excavation. More than fifty springs, wells, and streams were found in the tunnel area during the first investigation carried in July 2005, and fifteen of them including twelve springs, one well, and two streams, which either supply people with drinking water or flow at a notable rate, were finally selected to perform a long term monitoring program. In addition, discharge from tunnel and rainfall in the project area were monitored together. Figure 3 shows the location of the observation points included in the frequent sampling protocol.

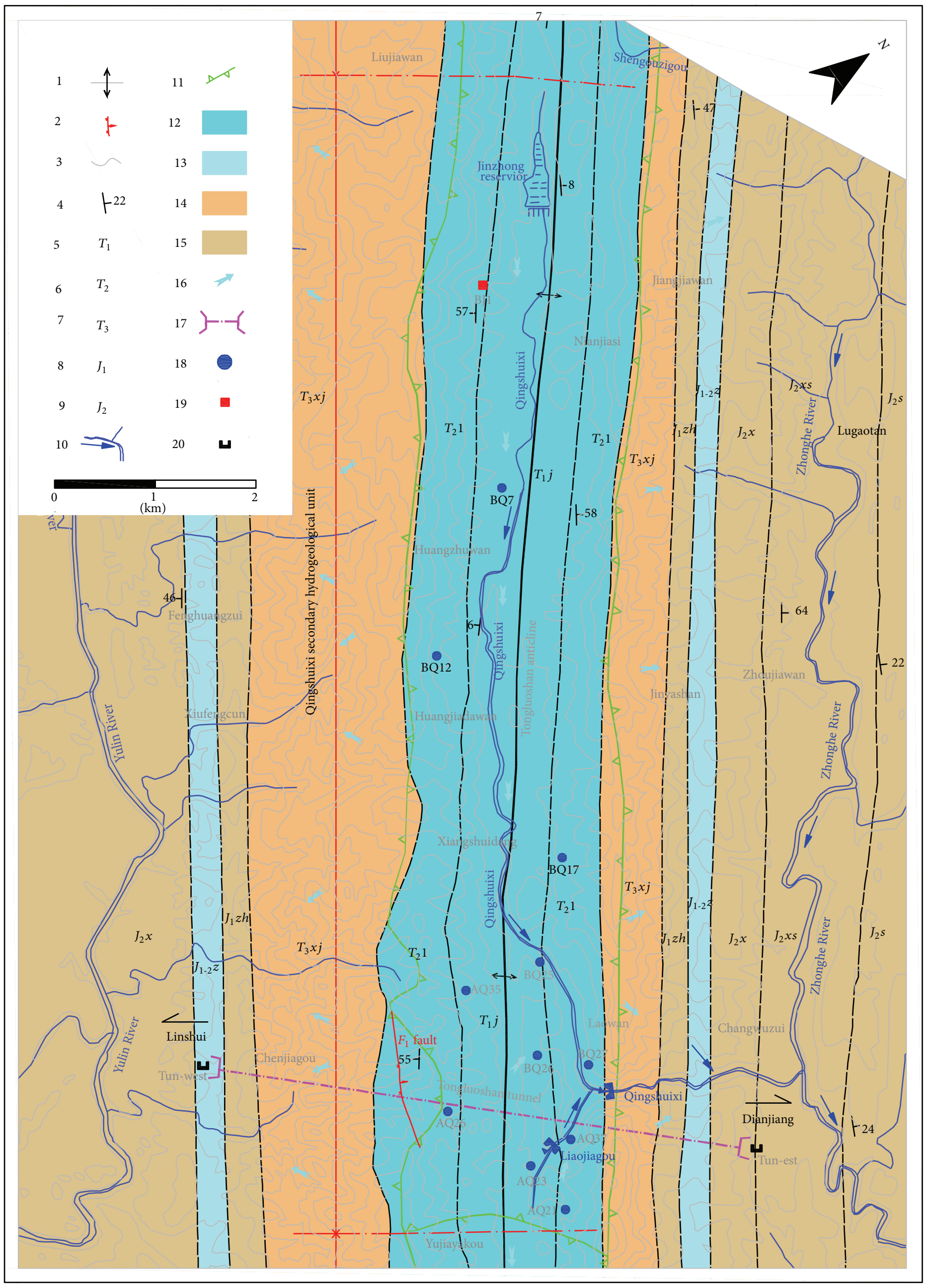

FIGURE 3: Map showing hydrogeological features and observation points in the project area. 1: anticline; 2: fault; 3: stratigraphic boundary; 4: attitude of strata; 5: lower Triassic; 6: middle Triassic; 7: upper Triassic; 8: lower Jurassic; 9: upper Jurassic; 10: river and its flow direction; 11: watershed; 12: limestone and dolomite; 13: carbonate rocks interbedded with mudstone; 14: sandstone; 15: mudstone interbedded with siltstone; 16: flow direction of groundwater; 17: tunnel; 18: spring; 19: well; 20: drainage from tunnel.

The monitoring process, lasting about 15 months from May 2006 to July 2007, was executed within the main construction period, during which daily discharge rate of tunnel and springs, flow of streams, and water table in well BJ1 were observed. In general, almost all the springs and streams as well as BJ1 respond to rainfall, with more responses from BJ1, BQ7, BQ27, AQ23, AQ37, Qingshuixi, and Liaojiagou, followed by BQ12, BQ25, AQ9, and AQ26. Another type including AQ21 and AQ35 shows evident time lag between discharge of springs and the precipitation, indicating that the fracture network recharging from rainfall and transferring groundwater to the emergence place does not work efficiently. More surprising, there are some springs which become nearly of no interest in precipitation, such as BQ17 and BQ26.

From a water balance point of view, it is believed that groundwater discharge from tunnel acting as a new flow out pattern will reduce the amount of other flow-out patterns such as springs and wells, supposing no changes happening

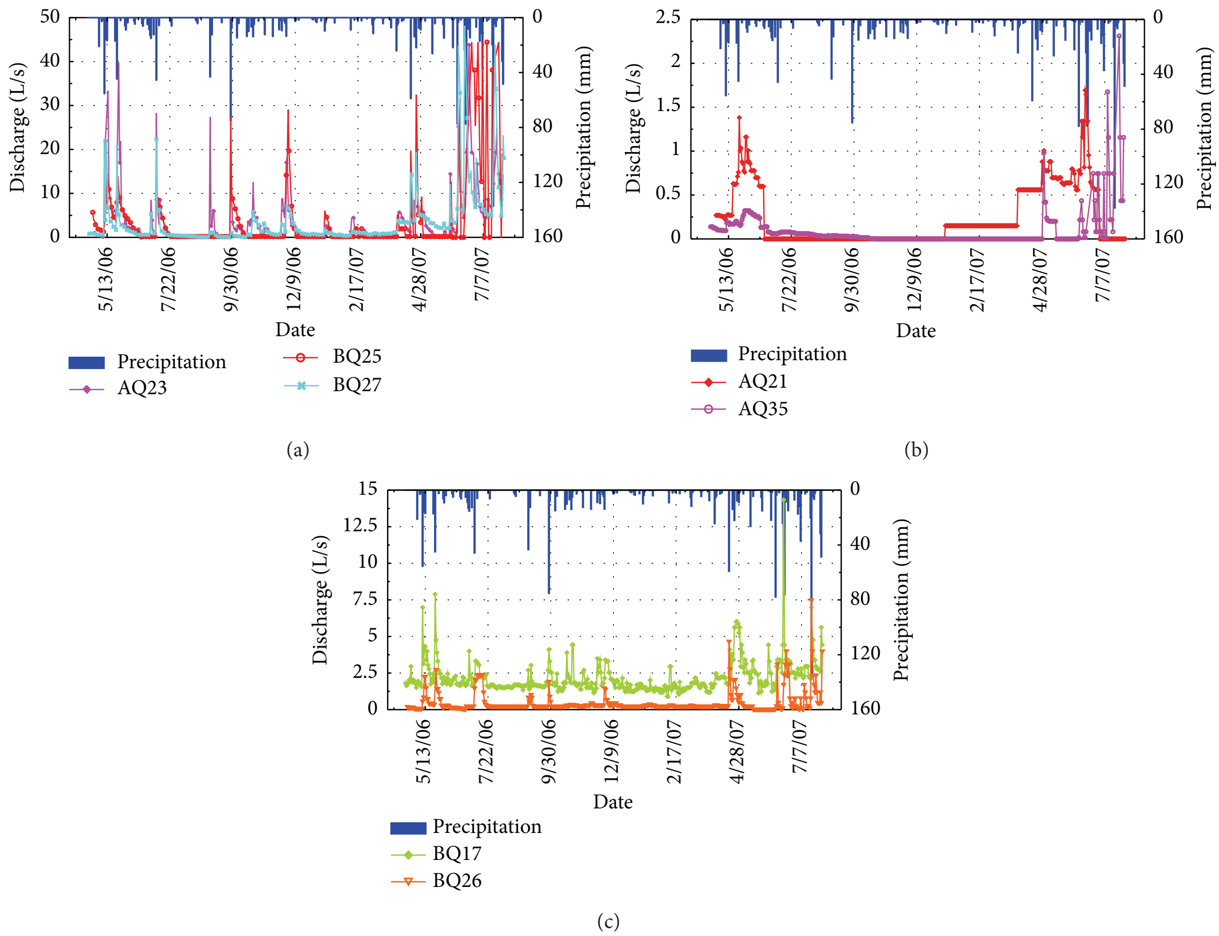

FIGURE 4: Hydrographs of the principal springs in the project area. (a) Discharge of AQ23, BQ25, and BQ27 versus time. (b) Discharge of AQ21 and AQ35 versus time. (c) Discharge of BQ26 and BQ27 versus time.

to the flow in patterns. Consequently, hydrograph of surface water and groundwater can help us to identify the influence caused by tunnel construction.

AQ23, BQ25, and BQ27 are karst springs which have never dried up in the past according to local residents, appearing in T_1j stratum. It is obviously described in Figure 4(a) that these springs respond quickly to rainfall, especially in some periods with sufficient recharge. However, unfortunate things happen to AQ23 and BQ25 during the monitoring period. AQ23 completely dried up during June 27 to 30, 2006, July 29 to September 4, 2006, September 16 to 27, 2006, December 22, 2006, to January 11, 2007, and March 15 to April 1, 2007. BQ25 had no discharge during July 23 to September 27, 2006, October 15 to November 28, 2006, December 10, 2006, to January 10, 2007, January 18 to February 12, 2007, February 23 to April 1, 2007, and May 1 to 31, 2007. These phenomena indicate that Tongluoshan tunnel may drain groundwater which could have come to surface from AQ23 and BQ25. Compared to them, BQ27 has more luck because it had never dried up despite the fact that the minimum flow rate was about 0.1 L/s, far below the normal average 0.8 L/s.

AQ21 flowed out from an abandoned mine, which settled in T_3xj coal bearing layer. It continuously supplied people around with groundwater for drinking prior to tunnel excavation. According to the records shown in Figure 4(b), the flow came to zero during June 22, 2006, to January 9 and July 1 to 31, 2007, in spite of adequate rainfall during January 10 to June 30, 2007. AQ35 is an epikarst spring situated in higher elevation, as is recorded in Figure 4(b); its discharge declined from 0.3 L/s to zero using approximately 4 months and maintains this status for a long time regardless of whether rainfall occurred. Based on the situation described above, it is doubted that AQ21 and AQ35 may had been linked to tunnel construction. According to Figure 4(c), BQ17 flowed throughout the period recorded with modest discharge, even during rainy periods. This phenomenon can be attributed to the abundant storage capacity of fractures that feeding BQ17.

Liaojiagou is a branch of Qingshuixi, which is the major stream in the project area. According to Figures 5 and 4(a), both Qingshuixi and Liaojiagou bear much resemblance to AQ23, BQ25, and BQ27 in response to rainfall. But Liaojiagou, as with AQ23, did not escape influences from both local meteorological condition and tunnel excavation. They

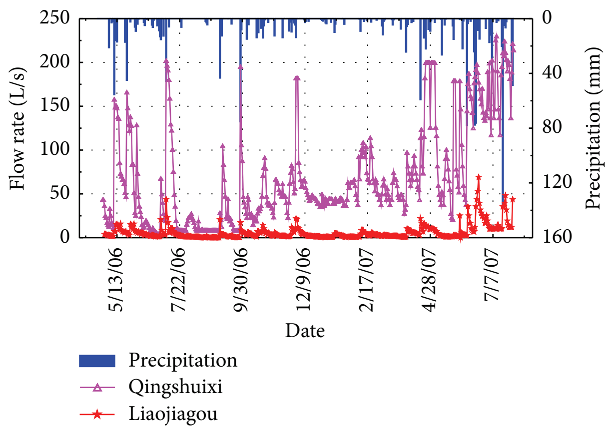

Figure 5: Hydrographs of Qingshuixi and Liaojiagou.

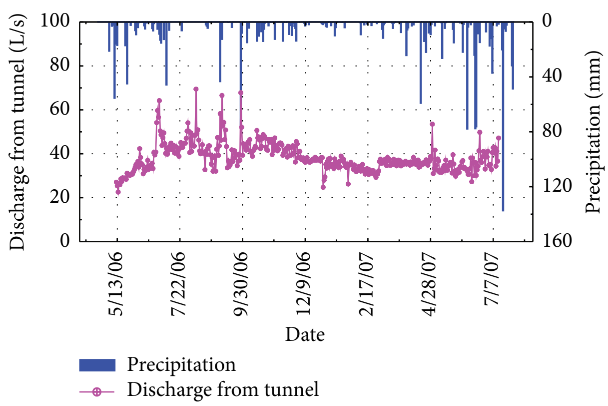

Figure 6: Drainage from tunnel versus time.

dried up quickly after being recharged from precipitation and continued this state for a long period. However, Qingshuixi showed strong vitality during the whole monitoring period, flowing in quite accordance with precipitation recorded in the project area without any appearance of external leakage, demonstrating that Qingshuixi has not been affected by construction of Tongluoshan tunnel.

Drainage from Tongluoshan tunnel is depicted in Figure 6, from which we can find a quick increase from 20 L/s to 64 L/s before June 28, 2006, and drastic oscillation between 32 L/s and 69 L/s in the next three months, followed by pediocratic changes between 30 L/s and 40 L/s. In general, tunnel inflow had an obvious ascending tendency when encountering carbonate rocks and performed a slow downtrend after drainage of groundwater stored in the fracture network around tunnel and grouting to prevent water inrush.

3.4. Determination of an Impact. While employing the indicator system to assess the negative effects caused by Tongluoshan tunnel construction on groundwater environment, maximum membership principle method makes an assessment result of medium level as 0.355 is the maximum member in the evaluation result vector, and weighted mean method gives nearly the same result because T is very close to 3. From a mathematic point of view, moderate grade is recommended as the influence level of Tongluoshan tunnel.

In order to verify whether the assessment is reasonable or not, environmental investigation and hydrological monitoring program was carried out in the tunnel area. Twelve springs, one well, and two streams, which either supply people with drinking water or flow at a notable rate, were selected to perform a 15-month-long monitoring process and so were the discharge from tunnel and rainfall in the project area. During the main construction period, some of the monitoring points near the tunnel axis, such as AQ21, AQ23, AQ35, and BQ27, have been strongly impacted by tunnel construction and lasting drainage of groundwater. Most of them have never dried up and maintained base flow even in the dry season, but an obvious decline was found throughout the monitoring period. Though strong relation exists between most of the monitoring points and precipitation, it seems that groundwater drainage from tunnel plays a nonnegligible role because some of the monitoring points repeatedly ran dry during the main construction period despite being recharged by precipitation. Based on the information fed back from environmental investigation and hydrologic monitoring carried out during the main construction period, approximately 1 km from the tunnel axis (not including BQ25 which is partly fed by upstream surface water) is inferred as the sphere of influence in the middle karst section of Tongluoshan tunnel, which is less than other typical karst tunnel, such as Yuanliangshan tunnel and Geleshan tunnel [8, 16].

As is analyzed above, moderate grade influence on groundwater system is considered to be an appropriate result for Tongluoshan tunnel construction for the reason that (a) assessment made from the indicator system and fuzzy comprehensive method falls into middle level; (b) some of the monitoring points near the tunnel axis which have never dried up and maintained base flow even in the dry season experienced an obvious decline throughout the monitoring period, revealing that the local groundwater environment might have been impacted by the tunnel excavation; (c) the sphere of influence in the middle karst section of Tongluoshan tunnel approaches approximately 1 km from the tunnel axis, which is less than other typical karst tunnels. So, there is no doubt that the local groundwater environment had been impacted by the excavation of Tongluoshan tunnel, but the influence level is moderate.

4. Conclusion and Outlook

Making an assessment on how the construction would affect local groundwater environment before excavation is of vital importance to line selection of tunnel. This study adopted an indicator system and fuzzy comprehensive evaluation method to identify the influence caused by Tongluoshan tunnel construction on groundwater environment. It was shown that maximum membership stood in the middle of the evaluation result set and 3.2 was scored by relative rating weighted calculation, indicating that excavation of Tongluoshan tunnel had influenced the local groundwater environment at a moderate degree. Based on the information fed back from environmental investigation and hydrologic monitoring carried out during the main construction period, flow of some springs and Liaojiagou stream located beside the tunnel route was found experiencing an apparent decline; even worse, AQ21, AQ23, AQ35, and BQ25 had dried up for a relatively long time because of lower precipitation during 2006 than that in the past and drainage from tunnel resulting in reduction of other flow-out patterns in water balance.

Through this practice, it can be concluded that making an assessment using the indicator system and fuzzy comprehensive evaluation method would supply us with a simple way to understand the situation that may happen to groundwater environment during tunnel construction and can help us to choose an optimized channel through which less disruption related to water inflow may occur. Once the tunnel location is determined and prepared to construction, we can also use the indicator system to evaluate the potential groundwater environmental impact before building it and take appropriate measures to minimize the impact. The major differences between a building tunnel and a built tunnel focus on two indicators including "construction method" and "measures for prevention of groundwater flowing into tunnel." Taking Tongluoshan tunnel as an example and setting "boring machine method" and "drainage with composite lining" as the initial condition, a result vector of 0.106, 0.195, 0.312, 0.242, and 0.145 indicates that the influence level partly tends to be strong, because the gap between the maximum member and the second maximum member falls to 0.07, smaller than 0.1. In order to minish the potential impact, measurements such as previous and postgrouting from tunnel, pregrouting from surface, and partial excavation using drilling and blasting method were taken at some sections with high risk of water irruption, reducing the influence level and impact on groundwater environment to some extent.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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